Multinuclear NMR Studies and *Ab Initio* Structure Calculations of Hindered Phencyclone Diels-Alder Adducts from Symmetrical Cyclic Dienophiles: Cyclohexene, Vinylene Carbonate, Vinylene Trithiocarbonate and Two *N*-Aryl Maleimides

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A series of hindered Diels-Alder adducts have been prepared from phencyclone, **1**, with various unusual symmetrical cyclic dienophiles, including cyclohexene, **2a**; vinylene carbonate, **2b**; vinylene trithiocarbonate, **2c**; and the *N*-aryl maleimides: *N*-(4-dimethylamino-3,5-dinitrophenyl)maleimide ("Tuppy's maleimide"), **2d**; and *N*-[3,5-bis(trifluoromethyl)phenyl]maleimide, **2e**. The highly hindered adducts, **3a-e**, respectively, were extensively characterized by one- and two-dimensional NMR methods, observing proton, carbon-13 and fluorine-19. High resolution COSY45 spectra permitted rigorous proton NMR assignments. The 2D heteronuclear C-H chemical shift correlation spectra (HETCOR, XHCORR) were obtained for adducts **3a-d**, allowing specific assignments for protonated carbons. Corrections to earlier proton NMR assignments for the vinylene carbonate adduct are given; results of the gated decoupling ^{13}C NMR experiment for this adduct supported *endo* adduct stereochemistry. Relative proton chemical shifts for bridgehead phenyls of adduct **3c** appeared anomalous relative to other adducts, suggesting possible special anisotropic interactions (with endocyclic sulfur or other anisotropic groups in the product) due to the unusual calculated orientation of the phenyls. The *unsubstituted* bridgehead phenyls in all adducts were shown to exhibit slow exchange limit (SEL) ^1H and ^{13}C spectra on the NMR timescales at ambient temperatures (7 tesla) showing slow rotations about the C(sp^3)-C(aryl sp^2) bonds. The rapid rotation of the N-aryl rings of the maleimide adducts was indicated by fast exchange limit spectra, suggesting that *ortho* substitution of the N-aryl ring may be necessary to slow this rotation to the SEL regime. *Ab initio* geometry optimizations at the Hartree-Fock level were carried out for each adduct, with the 6-31G* basis sets. Appreciable geometry differences were seen in calculated structures, and significant NMR chemical shift differences were experimentally observed, depending on the nature of the groups attached to the (*Z*)-HC=CH moiety of the dienophiles.

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Introduction.

The hindered adducts from the potent Diels-Alder diene, phencyclone, **1** [1], have been of considerable interest for NMR studies of hindered rotations and magnetic anisotropic shielding effects, *e.g.*, for the *N*-*n*-hexylmaleimide adduct [2]. For example, the *unsubstituted* bridgehead phenyls in many Diels-Alder adducts of **1** have been shown to exhibit slow rotations about the C(sp^3)-C(aryl sp^2) bonds on the NMR timescales based on slow exchange limit (SEL) proton or carbon-13 spectra at ambient temperatures (at 7 and 4.7 tesla, *i.e.*, 300 or 200 MHz for ^1H, 75 or 50 MHz for ^{13}C). Selected references include studies of the phencyclone adducts from *N*-*n*-propylmaleimide [3]; *N*-*n*-butylmaleimide [4]; *N*-carbamoylmaleimide [5]; *N*-pentafluorophenyl maleimide [6]; *N*-phenylmaleimide and *N*-(2-trifluoromethylphenyl)-maleimide [7]. Anisotropic effects on the bridgehead phenyls of the adducts are suggested by dispersion in proton chemical shifts of 1 ppm or more, a rather wide range for phenyl rings bearing no substituents or conjugated groups and connected only to a quaternary sp^3 carbon.

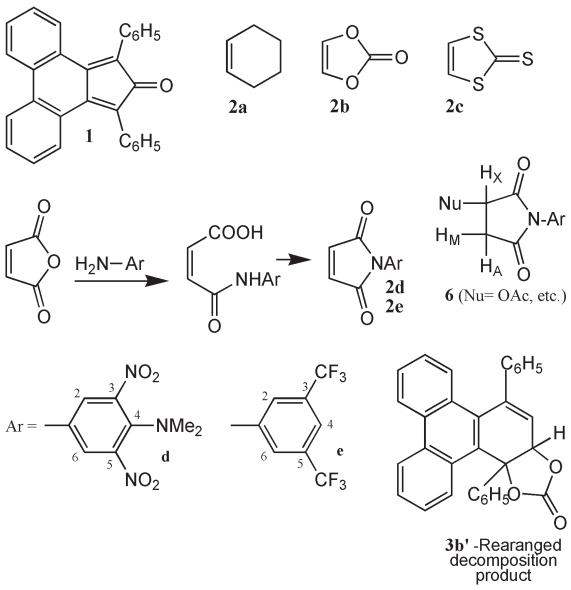

Figure 1. Structures and atom numbering for key reagents, precursors and possible side-products.

Depending on the nature of the dienophiles, **2**, used to form the adducts, **3**, rather dramatic anisotropic shielding effects may be seen for some nuclei derived from the dienophiles, positioned towards the phenanthrenoid moiety of the *endo* adducts, and experiencing shielding attributable to the phenanthrenoid rings, as with phencyclone adducts of *N*-(2,6-dialkylphenyl]maleimides [8] and a series of *N*-*n*-alkylmaleimides [9]. Structures and compound numbering are shown in Figures 1 (for **1** and **2**) and 2 (for the adducts, **3**). *Ab initio* calculations at the Hartree-Fock level have

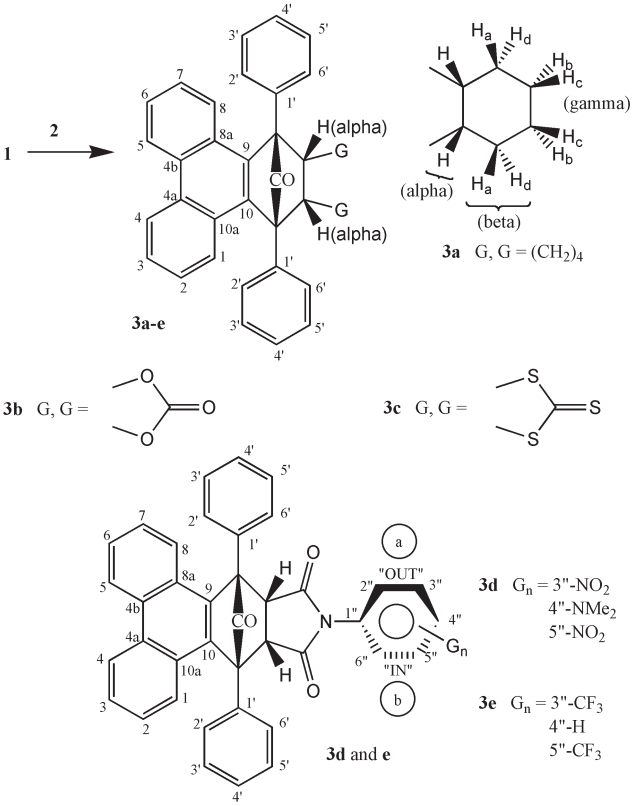

Figure 2. Structures and atom numbering for phencyclone adducts.

been carried out on the crowded adducts to gain insight into expected preferred conformations. This present report compares the phencyclone adducts from a diverse range of symmetrical cyclic dienophiles, with varied substituents on the (*Z*)-HC=CH bond of the dienophile. Here we examine adducts from cyclohexene, **2a**; vinylene carbonate, **2b**; vinylene trithiocarbonate, **2c**; and the *N*-aryl maleimides: *N*-(4-dimethylamino-3,5-dinitrophenyl)maleimide ("Tuppy's maleimide"), **2d**; and *N*-[3,5-bis(trifluoromethyl)phenyl]maleimide, **2e**. Geometry minimizations for the corresponding adducts, **3a-e**, were performed at the Hartree-Fock level with the 6-31G* basis sets. We believe that this is the first report describing the hindered bridgehead phenyl rotations of phencyclone adducts from a diverse assortment of symmetrical cyclic dienophiles in conjunction with high level (*ab initio*) structure calculations for the adducts.

EXPERIMENTAL

General synthetic procedures and spectral methods followed techniques described earlier [2-9]. Reagents were obtained from Aldrich Chemical (Sigma-Aldrich, Milwaukee, WI) and used directly without further purification. NMR spectra were routinely acquired with a Bruker AC300F spectrometer with Aspect 3000 data system, with observe frequencies of *ca*. 300 MHz for proton and 75 MHz for carbon-13. [Note that the proton NMR spectrum of *N*-[3,5-bis(trifluoromethyl)phenyl]maleamic acid was acquired at 400.13 MHz with a Bruker 400 AVANCE instrument.] NMR chemical shifts were referenced to internal tetramethylsilane (TMS) at 0.0 ppm for ^{1}H, to the central line of $CDCl_3$ at 77.0 ppm for ^{13}C, and to internal $CFCl_3$ at 0.0 ppm for ^{19}F. Standard 1D ^{13}C and ^{19}F NMR were obtained with composite pulse decoupling (WALTZ16) of protons. Normal relaxation delays (RD) were 1 sec for proton, 3 sec for carbon-13, and 5 sec for fluorine-19, unless noted. For the high resolution COSY45 spectra, the aryl proton region (typically *ca*. 700 Hz spectral width from about 6.6 to 8.9 ppm) was examined with 256 increments in the t_1 dimension, with 2 dummy scans and 16 transients per increment. For the HETCOR (XHCORR) spectra, typically 256 scans were acquired for each of 128 increments in t_1. For DEPT45 spectra, between 128 and 1024 scans were acquired. See Table 1 for proton shifts of adducts **3a-e**. Infrared spectra were acquired on KBr pellets with a Perkin Elmer 1640 or Midac M2000 spectrophotometer with DTGS detector at 4 cm^{-1} resolution; only major peaks are listed. Molecular modeling calculations were performed using Spartan '04 ESSENTIAL (v. 2.0.0, Wavefunction, Inc. ©1991-2003; Oct. 8, 2003) or Spartan '04 for Windows (full version, v. 1.0.0, Wavefunction, Inc. ©1991-2003; Sept. 17, 2003) on Dell Pentium 4 platforms with 2.4 or 3.06 GHz processor speeds and 512 or 1024 MB memory. Replicate calculations for several compounds were run using one or more of the available software packages to confirm reproducibility or locate the lowest energy optimized structures. Data presented here reflect the lowest energy calculations, regardless of the software or platform used. Calculation parameters included turning symmetry *off* and convergence *on*.

Phencyclone Adduct, **3a**, from Cyclohexene.

Cyclohexene was washed with aq. $NaHSO_3$ (3%) and dried (anh. Na_2SO_4). Phencyclone (1.0705 g, 2.799 mmol), 2,6-di-*tert*-butyl-4-methylphenol (BHT, *ca*. 3 mg) [2] and a magnetic stirbar were combined in a round-bottom flask with the purified cyclohexene (16.2675 g, 198 mmol), capped and stirred at ambient temperature for 3 weeks. Discharge of the intense green-black phencyclone color had not completed, so the cap was replaced by a water-cooled condenser, topped by a drying tube, and the system was refluxed for 2 days, resulting in decolorization of the mixture to a light yellow. Partial solvent removal (rotary evaporator) produced abundant crystals, collected and dried to give the crude adduct (693.3 mg, 53.1% yield). This material contained considerable cyclohexene (by proton NMR) and was recrystallized from CH_2Cl_2 – ethanol to give white crystalline flakes, used for NMR studies, with mpr

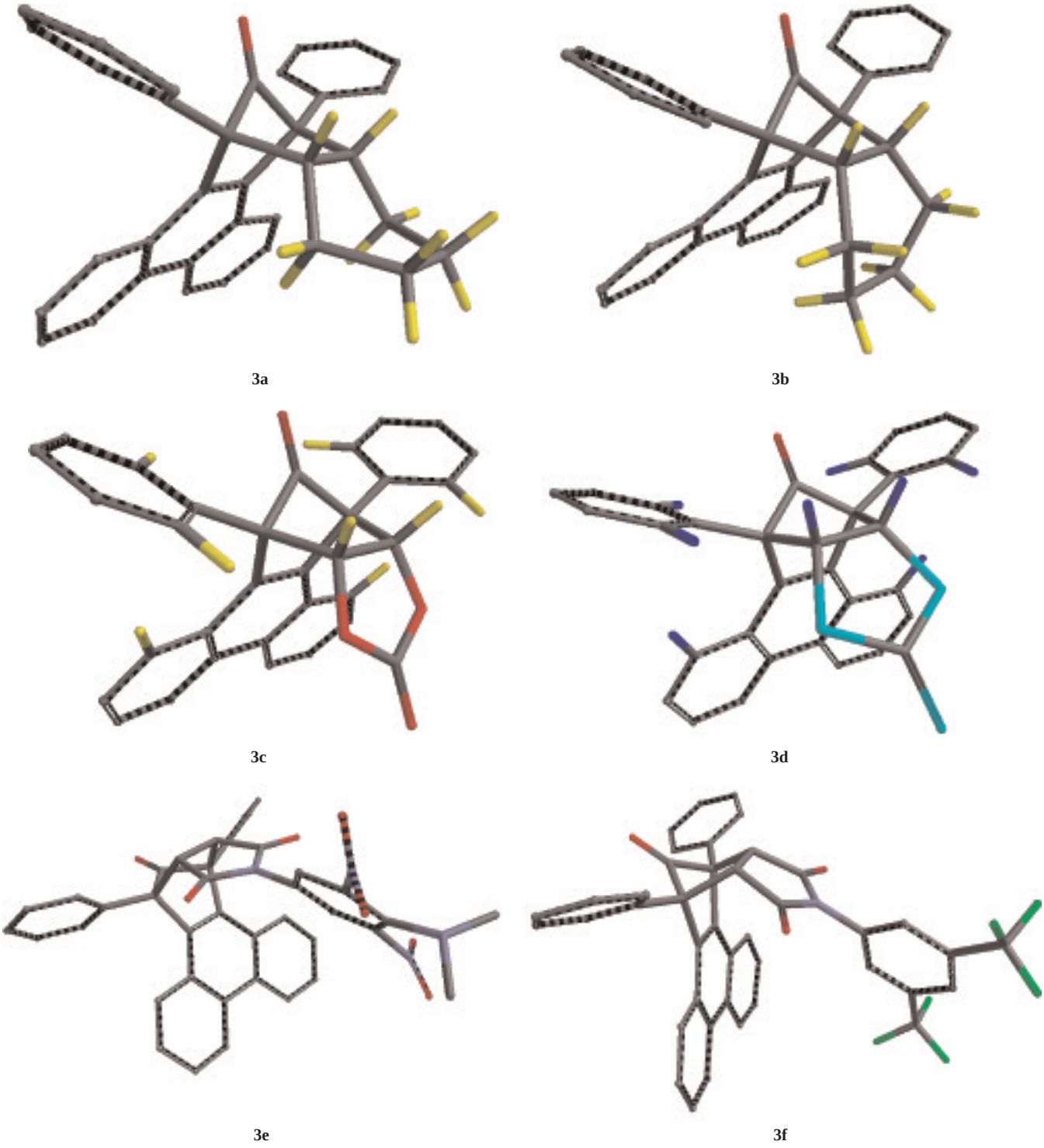

Figure 3. Calculated structures from Hartree-Fock/6-31G* geometry optimizations of the phencyclone adducts. (Selected hydrogens may be hidden for clarity.) (a) Cyclohexene adduct **3a** *anti*; (b) cyclohexene adduct **3a** *syn*; (c) vinylene carbonate adduct **3b**; (d) vinylene trithiocarbonate adduct **3c**; (e) Tuppy maleimide adduct **3d**; (f) *N*-[3,5-bis(trifluoromethyl)phenyl]maleimide adduct **3e**.

270-271° (dec., with darkening). ^{13}C ($CDCl_3$): 203.79 (ketone C=O); 136.39 Q; 135.98 Q; 131.92 C6'; 130.60 Q; 128.88 C3'; 128.56 C5'; 128.31 Q; 127.51 C4'; 126.62 C2'; 126.10 C2,7; 126.08 C3,6; 126.03 C1,8; 123.23 C4,5; 64.18 C_6H_5-*C*; 38.63 bridgehead sp^3 (alpha); 20.03 CH_2 (beta); 18.95 CH_2 (gamma).

Table 1

Proton NMR Shifts for Phencyclone Adducts of Cyclic Dienophiles, in ppm (with observed coupling constants in Hz) in $CDCl_3$. See Notes.

	3a	**3b**	**3c**	**3d**	**3e**
Nucleus					
H-1,8	7.08 (8.26,0.88)	7.00 (8.34)	6.91 (7.93)	7.15 (8.39)	7.16 (8.30)
H-2,7	7.21 (7.59)	7.20 (7.55)	7.21 (7.01)	7.24 (7.65)	7.24 (7.30)
H-3,6	7.54	7.56 (7.52)	7.57 (7.73,1.16)	7.57 (7.05,1.1)	7.56 (7.34)
H-4,5	8.74 (8.32)	8.70 (8.37)	8.73 (8.28)	8.67 (8.45)	8.66 (8.42)
H-2'	7.68 (7.75)	7.84 (7.73)	7.37 (7.70)	8.27 (7.85)	8.29 (7.84)
H-3'	7.58 (7.38)	7.70 (7.52,0.95)	7.65 (7.58,1.16)	7.73 (7.57)	7.73 (7.58)
H-4'	7.42 (7.20)	7.56 (7.52)	7.53	7.55 (7.34)	7.56 (7.34)
H-5'	7.35 (7.51,1.38)	7.47 (7.54,1.16)	7.45 (7.56,1.19)	7.47 (7.56)	7.47 (7.57)
H-6'	7.13 (7.72)	7.29 (7.76)	7.22 (7.01)	7.30 (7.81)	7.31 (7.82)
Bridgehead	3.31 m	6.08	6.01	4.61	4.66
H(a) beta	1.86 d (14.25)				
H(b), H(c)	1.52 br s				
H(d) beta	0.73 m				
H2",6"				6.30	6.33
H4"					7.54
$N(Me)_2$				2.62	

Notes: Approximate observed coupling constants are shown in parentheses, and refer usually to the gross vicinal (^3J) couplings. Fine splitting from long range couplings have been shown when seen for aryl proton signals. Gross multiplicities for the aryl protons (d or t) were consistent with the numbers of vicinal proton neighbors (one or two, respectively). The large coupling for H(a) of 3a is a geminal coupling.

Table 2

Calculated energies (atomic units) and geometric parameters for Diels-Alder adducts, including selected distances (angstroms) and dihedral angles (degrees). See Notes (below) and Discussion.

Adduct	Energies	Dihedral angles O=*C*-C-C1'-*C6*'	Interatomic distances H6'…ketone C=*O*	H2'…. bridgehead C*H*	H6'…H1	H2'…H1	Phenanthrene pucker
3a anti	-1416.5813400	59.41, -59.36	2.915, 2.914	3.218, 3.219	3.218, 3.219	3.333, 3.332	0.281
ΔE, kcal/mol	6.39						
3a syn	-1416.5711500	58.92, -58.99	2.896, 2.898	3.210, 3.209	3.210, 3.209	3.351, 3.353	0.287
3b	-1522.9257163	48.99, -49.01	2.669, 2.669	2.257, 2.257	3.444, 3.444	2.998, 2.998	0.248
3c	-2490.8310070	55.88, -55.84	2.812, 2.811	2.251, 2.252	3.289, 3.291	3.235, 3.234	0.257
3d	-2310.5204718	51.50, -53.07	2.707, 2.750	2.277, 2.274	3.406, 3.423	3.065, 3.069	0.286
3e	-2441.7687126	52.38, -52.70	2.730, 2.740	2.272, 2.269	3.237, 3.395	3.079, 3.080	0.268

Notes: Where pairs of values of a parameter are given, replicate measurements were obtained from corresponding nuclei on each "half" of the molecule. See Figures for atom numbering. Signs for dihedral angles depend on local chirality. Phenanthrenoid pucker is the distance from the midpoint of the line joining H2 and H7, to the midpoint of the C4a-C4b bond. (The midpoint of the line joining H2 and H7 was closer to the dienophile-derived group.).

Phencyclone Adduct, **3b**, from Vinylene Carbonate.

In a 50 mL round bottom flask was placed vinylene carbonate (877.6 mg, 10.199 mmol), 25 ml of toluene, phencyclone (3.607 g, 9.432 mmol), and a magnetic stirbar. The flask was fitted with a water-cooled condenser topped with a drying tube (anhyd. $CaCl_2$). The reaction mixture was initially dark green-black, becoming light orange-red after *ca*. 20 hr reflux with stirring. Partial solvent removal and cooling to room temperature gave white crystals, collected by vacuum filtration and dried (4.646 g, 105% crude yield). Preliminary proton NMR showed large amounts of toluene present. Toluene removal was achieved by treating an aliquot of the crude adduct (280.1 mg) with 10 ml portions of CH_2Cl_2 and removing solvent (rotary evaporator). Essentially toluene-free adduct (117.9 mg) was thus obtained and used for NMR studies. Mpr 243-245° (vigorous gas evolution and darkening). A separate batch of this adduct was prepared as per Harrison [10] with *ca*. 15 hr reflux in xylene [with substantial decolorization of the phencyclone in *ca*. 2 hr] and had mpr 275-277° (dec., gas evoln.). Lit. 264-266° (dec.) [10] (See Discussion.) IR (KBr): 1816 vs, carbonate; 1795 vs, strained ketone C=O; 1498 m; 1448 m; 1360 m; 1148 s; 1089 s; 962 w; 936 w; 756 s; 724 m; 698 s. ^{13}C ($CDCl_3$): 194.39 (ketone C=O); 153.52 (carbonate); 132.87 Q; 132.37 Q; 131.50 Q; 130.92 C6'; 129.54 C3'; 129.28 C5'; 128.87 C4' or 3,6; 127.51 C2'; 127.26 C4' or 3,6; 126.96 Q; 126.71 C2,7; 125.17 C1,8; 123.42 C4,5; 77.90 (bridgehead CH); 66.27 C_6H_5-*C*. (See Discussion for results of the gated decoupling ^{13}C NMR spectrum.).

Phencyclone Adduct, **3c**, from Vinylene Trithiocarbonate.

As in the preparation of adduct **3b**, above, vinylene trithiocarbonate (647.9 mg, 4.826 mmol) in 25 mL toluene with phencyclone (1.7253 g, 4.51 mmol) was refluxed with stirring for 36 hr.

Table 3
Additional calculated geometric parameters for adducts. Distances are in angstroms; angles and dihedral angles are in degrees. See Discussion and Notes from preceding Table 2 and below.

Adduct	Distances from Pt. 1 (center of middle ring of phenanthrenoid) to: H(a) out	H(d) in	H(c) out	H(b) in	Distances from H2' to: H(c) out	H(d) in	H(a) out
3a *anti*	4.477, 4.475	3.193, 3.191	5.906, 5.906	5.528, 5.525	3.654,3.653	3.677,3.677	2.280,2.280
3a *syn*	5.107, 5.108	4.413, 4.414	4.591, 4.591	2.965, 2.965	H(b) in 4.408,4.408	2.271,2.272	3.152,3.152
	Angles from Point 2 to Point 1 to specified nucleus:				Dihedral angles: *C*(Q)CHCH$_2$*C*H$_2$(γ)		O=*CC*(Q)CH*C*H$_2$(β)
3a *anti*	54.96, 54.99	63.83, 63.84	47.17, 47.21	64.14, 64.18	173.33, -173.34		-158.63, 158.57
3a *syn*	46.14, 46.14	53.67, 53.66	73.15, 73.14	77.83, 77.81	78.47, -78.45		-162.13,162.16
	H2' to -X-	H1 to -X-	*C*X$_3$ to Pt. 1	Pt.2-Pt.1-*C*X$_3$	CX$_3$ Planarity	Ring Planarity	
3b	2.767, 2.768	3.606, 3.606	3.694	57.90	0.006	0.005, 0.005	
3c	2.890, 2.890	3.616, 3.614	4.153	62.26	0.004	0.000, 0.000	
	Pt.1 - H6" (in)	Pt.2-Pt.1-H6"	H2' - NC=*O*	H1 - NC=*O*	N planarity	Dihedral angle O=*C*NC1"*C6"*(in)	
3d	3.809	95.40	2.562, 2.573	3.305, 3.214	0.009 N out	128.09, -50.58	
3e	3.646	97.32	2.575, 2.581	3.294, 3.255	0.010 N out	119.42, -59.48	

Notes: Point 1 is the midpoint of the line joining C8a and C10a, and is the approximate center of the central ring of the phenanthrenoid moiety. Point 2 is the midpoint of the C9-C10 bond. C(Q) is the quaternary sp^3 carbon, C$_6$H$_5$-*C*. CX$_3$ Planarity for adducts ***3b*** and **3c** refers to the -X-C(=X)-X- groups, expressed as the distance of the ***C***X$_3$ carbon from the plane defined by the three attached heteroatoms. Ring Planarity for adducts ***3b*** and ***3c*** refers to the distances of the endocyclic heteroatoms to the plane defined by the three carbons in the carbonate or trithiocarbonate ring. N planarity for the adducts ***3d*** and ***3e*** refers to the distance of the nitrogen from the plane defined by the three attached atoms. For the latter two adducts, the N atom was on the side of the plane away from the adduct cavity and phenanthrenoid nucleus.

The reaction mixture, although still somewhat green, was cooled to room temperature. Pale yellow-green precipitate was collected by vacuum filtration, washed with chilled CH_2Cl_2 and dried to give 1.126 g of light yellow adduct (48.7% yield) for spectral studies, mpr 269-279° (vigorous gas evolution and darkening). IR (KBr): 1784 vs, strained ketone C=O; 1497 m; 1446 s; 1437 m; 1243 br. m; 1071 vs, trithiocarbonate; 902 w; 886 m; 853 w; 784 m; 751 s; 735 m; 723 m; 693 s. ^{13}C ($CDCl_3$) (RD=60 sec, NS=5441): 219.95 (trithiocarbonate); 196.03 (ketone C=O); 135.23 Q; 133.42 Q; 131.39 Q; 131.26 C2,7 or 6'; 129.51 C3'; 129.30 C5'; 128.77 C4'; 127.43 Q; 127.03 C3,6; 126.92 C2'; 126.54 C2,7 or 6'; 125.83 C1,8; 123.43 C4,5; 66.85 C$_6$H$_5$-*C*; 63.92 (bridgehead sp^3 CH).

Phencyclone Adduct, **3d**, from N-(4-Dimethylamino-3,5-dinitrophenyl)maleimide ["Tuppy's maleimide"].

In a screw-cap vial (*ca*. 20 mL capacity) was placed a magnetic stirbar, phencyclone (383.8 mg, 1.001 mmol), Tuppy's maleimide (321.8 mg, 1.0508 mmol), BHT (*ca*. 3 mg) [2] and sufficient CH_2Cl_2 to bring the mixture level to within 3-4 mm of the vial lip. After capping with a Teflon©-lined cap, the mixture was stirred at ambient temperature, with the initial intense green-black color becoming brown-orange in 5 min and yellow-orange after 15 min. After a total 60 min stirring, the light yellow-orange mixture gave 383 mg of orange solid upon solvent removal, washing with cold CH_2Cl_2 and drying (55.6% yield), mpr (with slow heating): early darkening ca. 270°, then dec. with gas evolution 280-286°, sufficiently pure for NMR studies. ^{13}C ($CDCl_3$): 196.64 ketone C=O; 172.64 imide NC=O; 144.05 Q; 139.29 Q; 133.28 Q; 133.17 Q; 131.14 Q; 130.86 C6'; 129.49 C3'; 128.87 C5'; 128.78 C2'; 128.71 C4'; 127.68 C3,6; 127.12 C2,7; 127.03 C2",6"; 126.04 Q; 125.50 C1,8; 123.38 C4,5; 121.63 Q; 109.35 weak, unassigned impurity?; 63.59 C$_6$H$_5$-*C*; 44.86 sp^3 CH bridgehead; 41.97 NMe_2. Traces of unreacted Tuppy maleimide were suggested by weak peaks at 134.55 and 42.24 ppm, consistent with reported signals [11] at 134.50 (HC=CH or aryl C2,6) and 42.19 ppm (NMe_2).

N-[3,5-Bis(trifluoromethyl)phenyl]maleamic Acid.

This maleamic acid was prepared in the normal way [2,19] by reaction of maleic anhydride with equimolar 3,5-bis(trifluoromethyl)aniline in warm CH_2Cl_2, *ca*. 5-10 mmol scale, in 40-60% yields. Crude solid was obtained on trituration and standing, collected by filtration and washed with cold CH_2Cl_2. The dried white crystals had mpr 144-150°, lit. 163-165° [12]. ^{1}H ($CDCl_3$): 9.29 (1H, br s, NH); 8.12 (2H, sl br s, H2,6); 7.73 (1H, sl br s, H4); 6.52 (1H, d, J=12.80, half of AB q, *cis* HC=CH); 6.46 (1H, d, J=12.80, half of AB q, *cis* HC=CH). This sample was directly converted to the corresponding maleimide.

N-[3,5-Bis(trifluoromethyl)phenyl]maleimide.

Prepared by standard methods [13,14], by cyclodehydration of the precursor *N*-[3,5-bis(trifluoromethyl)phenyl]maleamic acid in acetic anhydride with anhydrous sodium acetate at 90-100° for *ca*. 1.5 hr. The reaction mixture had become deep reddish-black. After cooling and quenching with ice-water, the mixture was partitioned into CH_2Cl_2, extensively washed with 5% aqueous $NaHCO_3$ and water. The organic layer was separated and dried (anh. Na_2SO_4), and solvent removal gave the crude solid maleimide, **2e**, in ca. 20-30% yield. Recrystallization from EtOH gave white crystals, mpr 77-81°. ^{1}H ($CDCl_3$): 7.95 (2H, sl. br s, H2,6); 7.87 (1H, sl br s, H4); 6.95 (2H, s, HC=CH). ^{19}F ($CDCl_3$): -63.42 s. Impurity ca. 28% acetoxypyrrolidinedione: 5.55 (1H, dd, ^{3}J=9.06 and 5.06 Hz, AcOC*H*, H$_A$); 3.39 (1H, dd, ^{2}J=18.64, ^{3}J=9.06, H$_M$); 2.96 (1H, dd, ^{2}J=18.64, ^{3}J=5.06, H$_X$); 2.22 (3H, s, CH_3CO). See Discussion.

Phencyclone Adduct, **3e**, from *N*-[3,5-Bis(trifluoromethyl)-phenyl]maleimide.

This adduct has mpr 267-269° (dec. with vigorous gas evolution and darkening). ^{13}C ($CDCl_3$, 66,126 scans): 196.59 (ketone C=O); 172.64 (NC=O); 133.31 Q; 133.20 Q; 133.24 (q, ^2J=34.2, C3",5"); 132.14 Q (sl. br., NC1"); 131.17 Q; 130.88 (2 CH); 129.48 (2 CH); 128.85 (2 CH); 128.78 (2 CH); 128.69 (2 CH); 127.56 (2 CH); 127.02 (2 CH); 126.16 (br. q, ^3J=3.15, C2",6"); 126.04 Q; 125.57 (2 CH); 123.23 (2 CH); 122.26 (app. quintet, ^3J=3.73, C4"); 122.19 (q, ^1J=273.2, CF_3); 63.62 C_6H_5-*C*; 44.90 (2 sp^3 CH bridgehead). ^{19}F ($CDCl_3$): -63.75 s.

Results and Discussion.

The dienophiles **2a-d** were directly available commercially; phencyclone was prepared as described earlier [2]. Dienophile **2e** was prepared with standard methods (Figure 1) by reaction of maleic anhydride with 3,5-bis(trifluoromethyl)aniline, **4e**, to form the *N*-[3,5-bis(trifluoromethyl)phenyl]maleamic acid, **5e**. The intermediate **5e** underwent cyclodehydration in modest yield (see below) to give the corresponding maleimide, **2e**.

For each of the phencyclone adducts described here, the basic question of bridgehead phenyl rotation rates was addressed based on the ^1H and ^{13}C NMR spectra. Slow exchange limit (SEL) spectra, implying slow rotations of these *unsubstituted* bridgehead phenyls on the NMR timescales, should result in observation of nine signals (in the absence of coincidental overlaps) from pairs of aryl methines, 2×CH. Four of the pairs would derive from the phenanthrenoid nucleus, 1,8; 2,7; 3,6; and 4,5, and five pairs would result from the bridgehead phenyls, positions 2', 3', 4', 5', and 6'. (See Figure 2.) Fast rotation of the bridgehead phenyls would give fast exchange limit (FEL) spectra due to exchanging and averaging of the 2',6' pairs and the 3',5' pairs, resulting in just three expected CH signals from these phenyls, with 4:4:2 relative intensities.

With adduct **3a**, a simple tetramethylene chain, $(CH_2)_4$, links the two bridgehead methines (labeled "alpha" in Figure 2). For adducts **3b** and **3c**, the two bridgehead methines of the adducts are directly attached to heteroatoms, *i.e.*, -X-C(=X)-X-, where X = O or S. In the final set of adducts, **3d** and **3e**, the "alpha" bridgehead methines are bonded to carbonyls of the imide group, -C(=O)-N(Aryl)-C(=O)-. Thus, these selected adducts provide examples of a wide range of phencyclone adducts.

The initially obtained crude adduct, **3a**, from phencyclone with cyclohexene, contained considerable cyclohexene (by ^1H NMR, *ca*. equimolar with adduct), consistent with the reported propensity for some phencyclone adducts to form solvates [15-17]. We have sometimes removed complexed solvent from phencyclone adducts simply by repeated co-distillations with CH_2Cl_2 or $CHCl_3$, with a final co-distillation using $CDCl_3$ if desired to avoid [proton] NMR peaks of the proton-bearing solvents. It should be noted that Harano and co-workers [15-17] have published X-ray crystal structures for several of the phencyclone adducts, and their results provide strong support for the structures of the analogs we present here. Addition of a trace of BHT, a free-radical trap, in these preparations is expected to potentially suppress undesired free-radical reactions, such as free-radical additions to the maleimides, free-radical polymerizations of the maleimides, or a free-radical process of oxidative decarbonylation from phencyclone (leading to 9,10-dibenzoylphenanthrene byproduct) [2,18,19]. Reference [19] describes work with the phencyclone analog, 3,6-dibromophencyclone and its adduct from Tuppy's maleimide. Literature values for chemical shifts of cyclohexene (in $CDCl_3$) were: ^1H: 5.67 (HC=CH); 1.99 (allylic CH_2-C=C); 1.61 ppm (CH_2-CH_2C=C). ^{13}C: 127.21 (HC=CH); 25.21 and 22.70 ppm [11]. For the adduct, **3a**, from phencyclone with cyclohexene, the bridgehead methine (alpha) protons resonated at 3.31 ppm as a symmetrical multiplet (six lines), the diastereotopic (beta) CH_2 protons at 1.86 (H_a in Figure 2) and 0.73 ppm (H_d in Figure 2), and the diastereotopic (gamma) protons (H_b and H_c in Figure 2) appeared as a 4H broad singlet at 1.52 ppm (overlapped with the HOD signal). Adduct assignments were based on the COSY45 spectrum, in which the bridgehead methine showed strong crosspeaks to both the 1.86 and 0.73 ppm signals, but not to the 1.52 ppm signal. The 1.52 ppm signal correlated only with the 1.86 and 0.73 ppm signals, and the 1.86 and 0.73 ppm signals were strongly correlated to each other, consistent with their large ^2J(geminal) coupling. Based on these assignments, we believe that the 0.73 ppm signal may be attributed to the *syn* protons, H_d (Figure 2) directed "into" the adduct cavity and toward the phenanthrenoid moiety, where it could experience an anisotropic shielding magnitude of *ca*. 1.1 ppm relative to the *anti* geminal neighbors, H_a. In the ^{13}C spectrum of this adduct, no less than three partly overlapped signals for aryl CH pairs were seen between 126.03-126.10 ppm, not baseline resolved, but assignments could be made from the HETCOR spectrum. HETCOR CH crosspeaks were seen for the bridgehead (alpha) methines and for the (gamma) methylenes [with the 1.52 ppm proton signal]. We could not observe crosspeaks from the (beta) proton signals at 1.86 or 0.73 ppm to the carbon signal at 20.03 ppm, which we ascribe to signal-to-noise consequences. We note that the above ^1H and ^{13}C NMR assignments for adduct **3a** reflect the major spectral peaks; even after recrystallizations from CH_2Cl_2/ethanol, there appeared to be numerous smaller peaks, perhaps suggesting *ca*. 10% of a minor component. The other component may have been the stereoisomeric *exo* Diels-Alder adduct, but we have not attempted to rigorously define this. Reversibility of the Diels-Alder reaction with **1** is known for some dienophiles, and this could account for some formation of the *exo* isomer of adduct [1]. Cyclohexene adduct **3a** exhibits ^1H and ^{13}C NMR spectra supporting slow exchange limit (SEL) spectra, implying slow rotation of the bridgehead phenyls on the NMR timescales. The suggested preferred conformation of the cyclohexyl ring in the *endo* adduct is further discussed below.

Preparation and characterization of the phencyclone adduct of vinylene carbonate was of particular interest to us. In 1975, Harrison had reported that the reactions of various substituted cyclopentadienones with **2b** in refluxing bromobenzene for 24 hr yielded substituted phenols containing no carbonyl, rather than the normal Diels-Alder adducts. Phencyclone itself, however, was said to yield a carbonyl-containing compound rather than a phenol, but thermolysis of the normal adduct, **3b**, (Figure 2) gave a moderate yield of phenolic product [20]. [No data were given for adduct **3b**.] The intermediacy of **3b** (from reaction with **1**) was postulated, based on IR peaks at *ca*. 1770 and 1810 cm^{-1} [phase not stated] with subsequent decarbonylation and decarboxylation from the adduct to give the observed substituted phenol product. The high reaction temperature (bromobenzene boils at *ca*. 156°) and long reaction time were possible factors in the formation of the reported products. In a later report, Harrison and Ammon [10] elegantly clarified and extended the earlier findings. Refluxing **1** and **2b** in bromobenzene for 48 hrs produced the

isolated rearranged cyclic carbonate, **3b'**, (see Figure 1) as a result of decarbonylation from the intermediate adduct, **3b**, followed by a concerted [1,5] sigmatropic shift of carbonate. Under milder reaction conditions of reflux in xylene (bp *ca.* 140°) for 15 hrs, the authentic normal Diels-Alder adduct, **3b**, was obtained in good yield. The authors' published data [10] showed IR bands (paraffin oil) at 1815 and 1795 cm^{-1} and mpr 264-266° (dec). These IR bands are close to the values that we observed (in a different phase), and could be consistent with cyclic carbonate and strained bridging carbonyl group of the Diels-Alder adduct. Published IR spectra for vinylene carbonate (neat) showed bands at 1831.2 (very strong) and 1777.0 (shoulder, med.-strong); ethylene carbonate (as a melt) showed bands at 1861.2 (shoulder, med.), 1802.1 (very strong) and ca. 1775 (strong) [21]. The difference in our observed mpr (decomposition ranges) versus that reported earlier [10] may be attributed, in part, to differences in heating rates, because many phencyclone Diels-Alder adducts characteristically undergo decomposition at elevated temperatures, as by decarbonylation of the bridging ketone carbonyl. We also note that when we prepared a separate batch of the vinylene carbonate adduct following the Harrison procedure [10] with *ca.* 15 hr reflux in xylene, this sample displayed proton and carbon-13 NMR spectra essentially identical with the material obtained in refluxing toluene. But our product from xylene exhibited a decomposition range of 275-277°, closer to Harrison's value. It is possible that some difference in observed decomposition range may reflect the specific solvent used for the synthesis (and potentially complexed with the adduct sample), *e.g.*, toluene versus xylene.

Our greatest concern was the reported ^{1}H NMR data from Harrison and Ammon, which indicated an 18H aromatic multiplet from 7.05-7.83 ppm (plus a 2H singlet at 6.05 ppm for the bridgehead methines). We have found in our own earlier studies that the phencyclone adducts consistently display a very distinctive low-field 2H doublet at, *e.g.*, *ca.* 8.7 ppm, assigned to the phenanthrenoid H4,5 protons. (This signal may be considered as diagnostic for the phencyclone adducts that we have examined.) Thus, the NMR data for **3b** published earlier seemed questionable. But, perhaps most important to us, the earlier ^{1}H NMR work was carried out on a low field spectrometer with 60 MHz observe frequency, under which conditions there is inadequate dispersion to observe and assign the different adduct aryl proton signals, so that the question of potential SEL spectra from slow rotations of the bridgehead phenyls simply cannot be investigated. Together with the other aspects of the earlier work regarding **3b**, we were especially interested in rigorous NMR examination of the compound.

Our results for the proton spectra of **3b** confirmed our earlier findings for the highly deshielded H4,5 resonance. With the available dispersion of the 300 MHz spectrometer, the aryl proton region is quite simplified and is consistent with the highly symmetrical [near-mirror symmetry] Diels-Alder adduct structure of **3b**, but not consistent with the less symmetrical structure of the decarbonylated and rearranged cyclic carbonate, **3b'**, isolated after bromobenzene reflux by Harrison and Ammon. For the vinylene carbonate adduct, **3b**, ^{13}C NMR showed that the carbonate C=O chemical shift of 153.52 ppm was virtually identical to the reported value of 153.42 ppm for vinylene carbonate and close to the value of 155.58 ppm for ethylene carbonate [11]. Both ^{1}H and ^{13}C NMR of the adduct implied SEL spectra, consistent with slow rotation of the bridgehead phenyls.

With our vinylene carbonate adduct, **3b**, we employed the method of Warrener, *et al.* [22], to establish *endo* stereochemistry in the Diels-Alder adduct. Use of the "gated decoupling" ^{13}C NMR experiment, with broadband proton decoupling gated *off* during the FID acquisition, allows development of nuclear Overhauser enhancement in a fully proton-coupled carbon spectrum. The key signal is that of the strained bridging ketone carbonyl, C=O. In the normally expected *endo* Diels-Alder adduct, the bridgehead methine hydrogens are directed "upwards," away from the adduct cavity and the phenanthrenoid moiety, and towards the ketone C=O. The dihedral angle magnitudes of the bridgehead methine hydrogens relative to the ketone carbonyl, *H*-C-C-*C*=O, would be *ca.* 88.6° based on the *ab initio* HF/6-31G* calculations for **3b** (described below). For dihedral angles near 90°, the vicinal ^{3}J CCCH coupling should be very small, according to the Karplus relationship. For the hypothetical *exo* Diels-Alder adduct stereochemistry, the corresponding dihedral angle magnitudes from the bridgehead methine hydrogens to the ketone carbonyl were *ca.* 159.1° (semi-empirical AM-1 calculation). Warrener has reported that in such *exo* adducts, the observed vicinal ^{3}J CCCH coupling was *ca.* 5-9 Hz, with the ketone carbonyl signal appearing as a distinct triplet, in clear contrast to the *endo* adducts, which exhibited an unsplit singlet for the ketone C=O signal. Our sample of **3b** gave a clean, unsplit singlet, $w_{1/2}$ *ca.* 2.3 Hz or less, at 194.4 ppm for the ketone C=O in the gated decoupling ^{13}C NMR spectrum, fully consistent with the assigned *endo* stereochemistry.

Adduct **3c** from vinylene trithiocarbonate exhibited anomalous proton chemical shifts for the bridgehead phenyls, with the H2' resonance at surprisingly high field. For the other adducts, the shifts of the bridgehead phenyl protons appear at progressively higher field (toward TMS) in the sequence H2', to H3', to H4', to H5', to H6' (most shielded). In contrast, **3c** exhibited these shifts in the sequence H3', to H4', to H5', to H2', to H6' (most shielded). Our initial interpretation was that this might reflect the direct effect of the trithiocarbonate sulfur atoms with a proximal C2', perhaps as a consequence of the large sulfur atoms and their unshared electron pairs. We return to this in our Discussion below regarding calculated structures. The reported carbon-13 NMR shifts for reagent vinylene trithiocarbonate ($CDCl_3$) showed the C=S at 213.13 ppm and the HC=CH at 129.06 ppm. For ethylene trithiocarbonate, the C=S resonated at 228.52 ppm [11]. For the adduct, the C=S peak was extremely weak and was convincingly observed only with the long 60 sec relaxation delay; it appeared at 219.95 ppm, almost 7 ppm further downfield than in the reagent **2c**, but not as deshielded as in ethylene trithiocarbonate. Apparently, the shift of the C=S group is very sensitive to surrounding structure, much more so than the C=O of the analogous carbonate systems. The strong observed IR band (KBr) for our adduct **3c** at 1071 cm^{-1} is consistent with the strong band at 1063.5 cm^{-1} for ethylene trithiocarbonate (melt) [21].

The phencyclone adduct, **3d**, from *N*-(4-dimethylamino-3,5-dinitrophenyl)maleimide ["Tuppy's maleimide"] gave a ^{1}H NMR spectrum with a sharp 2H singlet at 6.30 ppm for the *ortho* H2",6" protons of the N-aryl ring, indicating fast rotation of the N-aryl. Relative to the reported chemical shift of 7.97 ppm for these protons in the maleimide itself [11], this suggests a magnetic anisotropic shielding magnitude in the adduct of *ca.* 1.67 ppm as a result of H2",6" adduct protons spending 50% of their time in the adduct cavity, towards the phenanthrenoid moiety. This "inside," or *syn*, orientation would correspond to the edge

(of the N-aryl ring) labeled (b) in the structure of **3d** shown in Figure 2. (Since the N-aryl rotation of a nominal 180° about the N(sp^2)-C(aryl sp^2) bond would constitute a twofold degenerate interconversion, each conformer would equally contribute a 50% share to the equilibrium system.) Presumably, if one of these *ortho* protons spent 100% of its time in the adduct cavity, *syn* with respect to the phenanthrenoid system, the proton might exhibit an anisotropic shielding magnitude of *ca*. 3.5 ppm, and would resonate near 4.5 ppm. This might be investigated experimentally by low-temperature NMR spectra, if the *N*-aryl rotation could be "frozen out" to provide SEL N-aryl spectra. The postulated 4.5 ppm shift would be in excellent agreement with the observed ^{1}H NMR spectrum (ambient temperature, 300 MHz) for the H-6" proton of the *N*-aryl ring in the phencyclone adduct from *N*-(2-trifluoromethylphenylmaleimide [7]. The C-13 spectrum of the adduct, **3d**, exhibited the ten predicted intense signals for the aryl CH pairs, as expected for a slow exchange limit system (of the two bridgehead phenyls) with fast exchange limit for the *N*-aryl ring. The HETCOR spectrum allowed assignment of all protonated aryl carbon signals, despite having three closely spaced signals between 128.71 – 128.87 ppm and a close pair at 127.03 and 127.12 ppm. The highest-field carbon-13 signal for protonated aryl (C4,5) correlates with the lowest field proton signal (H4,5). Of the seven ^{13}C signals attributed to adduct non-protonated aryl carbons (Q), five were of relatively greater area (19.5 to 28.1 area units) and two were much weaker (5.9 and 9.3 area units) [relative to average areas for each of the aryl methine pairs of 59.6 area units, with RD=3 sec]. Of the seven expected Q signals, five would be attributed to pairs of carbons and two to individual carbons (*ipso* C1" and *para* C4"). Since the N-aryl ring is itself rotating rapidly, we cannot draw conclusions regarding the rotation rate of the dimethylamino group about the bond to the N-aryl ring, *i.e*., the Me_2N-C(aryl sp^2) bond.

Published proton and carbon-13 NMR data for **2e** have appeared, for d_6-DMSO solutions [14], so our present data in $CDCl_3$ are complementary. Laschewsky and co-workers had reported the ^{19}F NMR absorption for a $CDCl_3$ solution at -60.55 ppm, somewhat different from our observed value of -63.42 ppm, but fluorine chemical shifts can be temperature- and concentration-dependent. Our observed proton NMR of *N*-[3,5-bis(trifluoromethyl)phenyl]maleimide, **2e**, exhibited slightly broadened singlet signals for the aryl protons, consistent with small unresolved long-range H-H or H-F couplings. This crude maleimide showed proton absorptions consistent with substantial amounts of the (undesired) acetoxypyrrolidinedione side-product, **6** (Figure 1, Nu = OAc) [23], with the three 1H dd patterns of the AMX system and the 3H singlet of the acetate group. The aryl protons of the acetoxypyrrolidinedione partly overlapped with the resonances of the target maleimide. In our hands, the traditional method for maleimide formation by cyclodehydration of the precursor maleamic acid using anhydrous sodium acetate in acetic anhydride (at 90-100°) gave cleaner (*i.e*., solid) crude product than the alternative method of Wang [23], which initially gave an oil.

For the phencyclone adduct, **3e**, from *N*-[3,5-bis(trifluoromethyl)phenyl]maleimide, we have tentatively assigned the weak signal in the carbon-13 NMR at 132.14 ppm to NC1" (the *ipso* carbon) of the N-aryl ring, because of its slightly broadened appearance ($w_{1/2}$ = 2.3 Hz), which could be attributed to small unresolved long-range ^{4}J coupling to fluorine. The slightly broadened approximate quartet assigned to the C2",6" carbons reflects predominant vicinal couplings to the CF_3 fluorines. The sharper approximate quintet assigned to C4" is consistent with splitting by an even number of vicinal fluorines (*i.e*., the six fluorines of the 3,5-bis-(CF_3) groups). The ^{19}F NMR with proton decoupling shows one sharp singlet ($w_{1/2}$ *ca*. 1.4 Hz). Together with the proton NMR results, we conclude that *N*-aryl rotation is fast on the proton, carbon-13 and fluorine-19 NMR timescales. Bridgehead phenyl rotation is slow. Relative to the H2,6 proton resonances of the precursor maleimide, which resonate at 7.95 ppm, the H2",6" signal of the adduct appears at 6.33 ppm, implying an anisotropic shielding magnitude of *ca*. 1.6 ppm for the protons as a consequence of their spending half their time directed "into" the adduct cavity, toward the phenanthrenoid moiety. This is consistent with results described above for adduct **3d** and earlier data [7]. The change in chemical shifts from the ^{19}F NMR for the maleimide, **2e** to adduct, **3e**, were minimal, *ca*. 0.3 ppm.

For all five of the adducts described here, the relative ^{1}H NMR shifts of Table 1 seem quite striking with respect to the consistency of the shifts from adduct to adduct for some of the protons of the phenanthrenoid and bridgehead phenyls, and the much larger variations for other protons. The absorption for H2' of the phenyls is most unusual. This signal appears as far upfield as 7.37 ppm for **3c** (considered anomalously high field relative to all the other adducts), and as far downfield as 8.29 ppm for **3e**, a range of 0.92 ppm. The next largest range was 0.25 ppm for H1,8. The ranges for the other protons were as follows (in ppm): H2,7 (0.04); H3,6 (0.03); H4,5 (0.08); H3' (0.15); H4' (0.14); H5' (0.12); H6' (0.18). It is tempting to consider that the protons H2' and H1,8 with the largest ranges might be [spatially] closest to the varying substituents on the (alpha) sp^3 bridgehead methines, and therefore most susceptible to possible anisotropic effects. Alternatively, the generally larger shift ranges for the bridgehead phenyl protons (relative to, *e.g*., the phenanthrenoid H2,7; H3,6; H4,5), may reflect varying conformations of the phenyls with respect to their dihedral angles relative to the ketone carbonyl. To further explore possible adduct structures, we carried out geometry optimizations for **3a-e**.

Ab Initio Calculations.

For each of the phencyclone adducts, *ab initio* structure calculations were performed at the Hartree-Fock level with the 6-31G* basis set. This method is considered to provide reasonable accuracy for energies and conformer structures with respect to required calculation times [24-27]. Selected geometric parameters from these optimized structures are presented in Tables 2 and 3. Several calculated geometric parameters are defined here and evaluated for characterization of the adduct structures. The center of the middle ring of the phenanthrenoid moiety, Point 1, is defined as the midpoint of the line joining C8a and C10a. Point 2 is the midpoint of the C9-C10 bond. Distances (in Angstroms) from selected nuclei to Point 1 are provided, as well as some angles from Point 2 to Point 1 to specified nuclei. "Puckering" of the phenanthrenoid moiety refers to the butterfly-like folding of this aryl system, with the outer rings ("wings") folded towards the portion of the adduct derived from the dienophile. Pucker magnitude is expressed as the distance between the midpoint of the line joining H2 and H7, and the midpoint of the C4a-C4b bond. Another key parameter expresses the dihedral angles of the bridgehead phenyls relative to the strained bridging ketone carbonyl. The tabulated dihedrals express the smaller magnitude values measured from the carbon of the ketone carbonyl to the

bridgehead phenyl carbon (designated C6') directed "upwards" and proximal to the ketone, *i.e*., O=*C*-C(sp^3)-C1'(ipso)-*C6'*. Note that the observed pairs of dihedral angles reported have opposite signs reflecting the local chiralities of each "half" of the adduct. For adducts **3b** and **3c**, non-planarity in the –X-C(=X)-X- group is expressed as the distance from the central carbon to the plane defined by the three bonded heteroatoms. Both of these adducts show 0.006 Å or less of non-planarity by this measure. The Ring Planarity of these adducts measures "envelope folding" of these five-membered heterocycles; they are highly planar. For the maleimide adducts, **3d** and **3e**, non-planarity at the nitrogen is expressed as the distance from the nitrogen to the plane defined by the three directly bonded atoms. This N-planarity for each of the latter adducts was *ca*. 0.01 Å, with the nitrogen directed "outwards," and the *N*-aryl rings actually bent "inwards" toward the phenanthrenoid system.

For the cyclohexene adduct, **3a**, two different minima were located, referred to as the *anti* (lower energy) and the *syn* (higher energy) conformers, differing in the orientation of the "boat-like" conformations of the tetramethylene chain. For the more stable *anti* structure, the (gamma) $(CH_2)_2$ bridge is further from the phenanthrenoid central ring; in particular, the (beta "in") hydrogens, H_d, are relatively close to the center of that ring (Point 1, defined above), within 3.19 Å, and proximal (63.8°) to the axis perpendicular to the plane of the phenanthrenoid central ring and passing through the ring center. Anisotropic shielding effects should be favored for the H_d protons in this orientation [28]. In contrast, the **3a** *syn* conformer would have the H_b (gamma "in") protons calculated as closest to the middle of the phenanthrenoid central ring. Tabulated data for the **3a** conformers includes distances from H2' to each of the (beta) protons, H_a and H_d, and to the closer of the (gamma) protons. The closer (gamma) proton is H_c "out" for **3a** *anti* and H_b "in" for **3a** *syn*. The calculated energy difference, ΔE, for the **3a** *anti*/*syn* pair was 0.01019 au or 6.39 Kcal/mol (1 au = 627.5 Kcal/mol). This relatively large energy difference implies that the *anti* conformer would be overwhelmingly favored at equilibrium, which would be consistent with the appreciable shielding for the H_d (beta "in") proton signal assigned at 0.73 ppm versus the H_a (beta "out") signal assigned to the lower field 1.86 ppm absorption. Calculated structures for the **3a** *anti*/*syn* pair are shown in Figures 3a and 3b, with aryl hydrogens hidden for clarity.

The vinylene carbonate adduct, **3b**, appeared to be strikingly different from the *anti* cyclohexene adduct in several respects. The dihedral angles, O=*C*-C-C1'-*C6'*, for the bridgehead phenyls are more than 10° smaller for the vinyl carbonate adduct, bringing H6' of the phenyls closer to the bridging ketone oxygen (2.67 Å in **3b** versus 2.91 Å in **3a** *anti*) and bringing H2' of the phenyls much closer to the phenanthrenoid H1 (3.00 versus 3.33 Å). Increased anisotropic contributions might be expected from the closer proximities.

Duplicate optimizations for the adduct, **3c**, from vinylene trithiocarbonate, showed close agreement in the optimized energies, to within *ca*. 0.0000033 au. Comparing **3b** to **3c**, nearly 7° greater dihedral angles, O=*C*-C-C1'-*C6'*, for the bridgehead phenyls are seen for the trithiocarbonate adduct, bringing H6' closer to the phenanthrenoid H1 (3.29 versus 3.44 Å) and H2' further from H1 (3.23 versus 3.00 Å); the greater H2' to H1 distance might decrease deshielding by the phenanthrenoid and partly account for the higher field chemical shift observed for H2' in **3c**. Also, longer bond lengths to sulfur would account for greater distances from H2' to the endocyclic heteroatoms for **3c**, 2.89 versus 2.77 Å, which might also influence direct anisotropic effects. Calculated structures for adducts **3b** and **3c** are shown in Figures 3c and 3d, with the bridgehead methines, phenanthrenoid hydrogens H1,8 and bridgehead phenyl hydrogens H2' and H6' included to highlight potential interactions.

For the adduct **3d**, from Tuppy's maleimide, three separate optimizations were performed, with two showing relatively good agreement to within 0.000062 au (0.039 Kcal/mol), and one appreciably higher (by 0.0008814 au, 0.55 Kcal/mol). The optimized structures appeared to differ mainly in the conformations of the $–NO_2$ and $–NMe_2$ groups on the *N*-aryl ring. Some notable features of the *N*-aryl ring substituents follow. The plane of the *N*-aryl ring was defined by carbons C1", C3", C5", and the planes of each nitro group were defined by the NO_2 atoms. For the "inner" nitro (on the (b) edge of the *N*-aryl ring at the 5" position), the angle between the *N*-aryl and the NO_2 planes was 41.44°; the corresponding angle was 49.62° for the "outer" nitro at the 3" position (on the (a) edge of the *N*-aryl ring). The observed dihedral angle from the innermost oxygen of the "inner" 5"-nitro to C4", i.e., *O*=N(O)-C5"-*C4"*, was -140.72°. For the "outer" 3"-nitro, the dihedral angle from the oxygen *syn* to the ketone C=O to C4", i.e., *O*=N(O)-C3"-*C4"*, was 130.20°. The nitrogen of the $–NMe_2$ group was quite pyramidalized with the nitrogen located 0.252 Å from the plane of its three directly bonded neighbors. The $–NMe_2$ group was highly skewed with respect to the *N*-aryl ring. The tabulated data correspond to those for the lowest energy of the three calculations.

The most striking difference between adducts **3d** and **3e** (from *N*-[3,5-bis(trifluoromethyl)phenyl]maleimide) appeared to be in the relative angles between the *N*-aryl rings and the pyrrolidinedione rings. These angles were estimated from the calculated dihedral angles from the imide C=*O* to the ("inner") C6" of the N-aryl, O=*C*-N-C1"-*C6"*. The *N*-aryl and imide rings were closer to coplanarity for **3d** by about 9°, *i.e*., *ca*. 50° between the rings for the Tuppy's maleimide adduct and 59° for **3e**. This would account for the "inner" *N*-aryl H6" in **3e** being closer to the center of the middle ring of the phenanthrenoid moiety (Point 1), 3.65 versus 3.81 Å, and presumably should make it somewhat more shielded. This does not appear to be experimentally verifiable, however, since the apparent anisotropic shielding magnitudes determined by comparing *N*-aryl *ortho* proton chemical shifts in the adducts and the precursor maleimides may indicate the contrary. Thus, the published ^{1}H NMR spectrum for Tuppy's maleimide [11] shows the aryl proton resonance at *ca*. 7.97 ppm while the corresponding adduct signal for **3d** is at 6.30 ppm implying a shielding magnitude of about 1.67 ppm. For the bis-trifluoromethyl adduct **3e**, the *N*-aryl *ortho* proton signal appears at 6.33 versus 7.95 ppm for the maleimide, **2e**, indicating a slightly smaller shielding magnitude of 1.62 ppm. It may be that attempting to reconcile the apparent shielding magnitudes in the adducts with the distances of H6" to Point 1 is an oversimplification, since the angle Point 2 to Point 1 to H6" is greater in **3e** (97.3°) than in **3d** (95.4°), and the latter angle, closer to 90°, might tend to enhance anisotropic shielding. Lastly, we note that in **3e**, for the "inner" 5"-trifluoromethyl group, the fluorine closest to Point 1 is 5.232 Å away. Dihedral angles from each fluorine of this CF_3 group to C4" were 148.22, 27.76, and -91.96°. Calculated structures for adducts **3d** and **3e** are shown in Figures 3e and 3f, with all hydrogens hidden for clarity.

Conclusions.

A series of five phencyclone adducts, **3a-e**, have been prepared from a diverse group of symmetrical cyclic dienophiles, including cyclohexene, vinylene carbonate, vinylene trithiocarbonate, Tuppy's maleimide and *N*-[3,5-bis(trifluoromethyl)phenyl]-maleimide, with detailed proton NMR assignments for the adducts obtained by high resolution COSY45 spectra for each adduct, and assignments for protonated carbons obtained by HETCOR spectra for adducts **3a-d**. Spectra were obtained at ambient temperatures at 300 MHz for proton, 75 MHz for carbon-13, and 282 MHz for fluorine-19 (for adduct **3e**). For all five adducts, bridgehead phenyl rotation was slow on the proton and carbon-13 NMR timescales, with slow exchange limit spectra observed. In contrast, *N*-aryl rotations for both adducts, **3d** and **3e**, from the *N*-aryl maleimides, were fast based on sharply averaged fast exchange limit spectra for proton and carbon-13 NMR (and ^{19}F NMR, for **3e**), suggesting that *meta* disubstitution at the *N*-aryl C3",5" positions is not sufficient to retard the *N*-aryl ring rotation. Substantial anisotropic shielding of the *N*-aryl *ortho* H2",6" protons in **3d** and **3e** is consistent with the expected effect of the phenanthrenoid moiety, with each of the H2",6" protons spending half their time in a conformation placing them proximal to the central aromatic ring of the phenanthrenoid. Geometry optimizations for all five adducts were performed at the Hartree-Fock level with the 6-31G* basis set. Two distinct conformers were found for the cyclohexene adduct, with the more stable **3a** *anti* more consistent with proton assignments. A substantial range of adduct geometries for the calculated structures was found, especially with respect to the conformations of the bridgehead phenyls relative to the bridging ketone carbonyl. Some anomalous chemical shifts in the vinylene trithiocarbonate adduct were found (relative to the other adducts). The calculated structures, for the cyclic carbonate and trithiocarbonate rings in adducts **3b** and **3c** were highly planar. The *N*-aryl rings of the maleimide adducts were twisted by *ca*. 50-59° away from coplanarity with the planes of the imide systems. Proton NMR assignments for the vinylene carbonate adduct presented here differ somewhat from an earlier report. The *endo* stereochemistry in this adduct was confirmed by the sharp, unsplit singlet signal for the ketone C=O carbon in the gated decoupling ^{13}C NMR spectrum. Lastly, we would like to mention some suggestions from the Reviewers that might be very fruitful for further studies, including variable temperature (VT) NMR studies and GIAO (Gauge Independent Atomic Orbital) calculations for chemical shifts; our available NMR hardware did not allow us to do the VT experiments and our current computational software does not provide GIAO calculations. A second Reviewer suggested the use of the powerful NMR techniques of HMQC, HSQC, EXSIDE, HSQMBC, *etc*., which could not be performed on our present instrument. We are grateful for these suggestions.

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