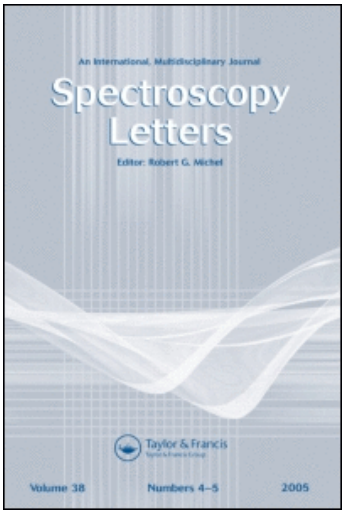

Spectroscopy Letters
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713597299

AB INITIO STUDIES OF HINDERED ROTATION OF SOME AROMATIC RINGS IN *N*-2,6-DIFLUOROPHENYL IMIDES AND UNSUBSTITUTED BRIDGEHEAD PHENYLS

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Online publication date: 21 March 2001

To cite this Article Langowski, Bryan A. , Rothchild, Robert and Sapse, Anne-Marie(2001) 'AB INITIO STUDIES OF HINDERED ROTATION OF SOME AROMATIC RINGS IN *N*-2,6-DIFLUOROPHENYL IMIDES AND UNSUBSTITUTED BRIDGEHEAD PHENYLS', Spectroscopy Letters, 34: 2, 235 — 251
To link to this Article: DOI: 10.1081/SL-100002012
URL: http://dx.doi.org/10.1081/SL-100002012

SPECTROSCOPY LETTERS, 34(2), 235–251 (2001)

AB INITIO STUDIES OF HINDERED ROTATION OF SOME AROMATIC RINGS IN *N*-2,6-DIFLUOROPHENYL IMIDES AND UNSUBSTITUTED BRIDGEHEAD PHENYLS

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ABSTRACT

Ab initio calculations are applied to the study of steric hindrance upon rotation of aromatic rings in *N*-2,6-difluorophenylmaleimide, 2, and in 3, which represents a simplified model of a Diels-Alder adduct of phencyclone and 2. The systems adopt geometries minimizing the hindrance in a number of ways, including pyramidalization of the nitrogen in the *N*-aryl imide and deviation from planarity of the aryl rings. Note: All designated Structures for Compounds 1 through 3 are shown in Figure 1.

Key Words: Hindered rotation; Phencyclone; Diels-Alder adducts; Maleimides; Ab initio calculations; *N*-2,6-difluorophenyl imides.

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INTRODUCTION

The significance of hindered bond rotations in chemistry can hardly be overstated. The research areas in which rotations about covalent single or double bonds are relevant cover a very wide range. Within the last year, for example, two notable articles discussed unidirectional intramolecular rotations, of interest for possible "molecular motors." In one case, rotation occurred about a single bond joining an sp^3 bridgehead carbon of a triptycene moiety and an sp^2 carbon of a helicene unit (1). In the second case, controlled rotation about a carbon-carbon double bond in a chiral, helical alkene was achieved by thermal and photochemical reactions (2). In part, studies of "molecular motors" spring from an interest in "biological motors" such as flagella or cilia (3).

Several other recent papers of considerable novelty have appeared, revealing a unique solvent-dependent atropisomerism within a hindered biaryl moiety of an antibiotic (4) or describing the role of hindered biaryl rotations in a synthesis of (-)-steganone and analogs (5). The papers cited above (and articles referenced therein) suggest the wide range of hindered rotation studies.

For several years, we have examined some unusual examples of hindered rotations and magnetic anisotropic effects in a series of Diels-Alder adducts of phencyclone, 1. In these compounds, we reported hindered rotations about the $C(sp^2)$-$C(sp^3)$ bonds to *unsubstituted* bridgehead phenyl groups, with slow rotations on the NMR time scale for room temperature medium field proton and carbon-13 NMR (6). Use of *N*-pentafluorophenylmaleimide as dienophile for addition to 1 provided an adduct which displayed five separate fluorine-19 NMR resonances (at 282 MHz) (7), implying hindered rotation about the *N*-aryl bond. *Ortho*-fluorine substitution on the aromatic rings of *N*-aryl maleimides, including *N*-2,3,5,6-tetrafluorophenyl maleimide and *N*-4-bromo-2,3,5,6-tetrafluorophenylmaleimide, also result in demonstrable hindered *N*-aryl bond rotations in the corresponding adducts with 1 (8). We also note that hindered *N*-aryl rotation in some *ortho*-substituted *N*-phenylmaleimides (and analogs) has been considered in connection with potential utility for asymmetric synthesis (9). Also, recent studies by Harano and coworkers (10) have described phencyclone Diels-Alder adducts with several *N*-substituted maleimides, including some *N*-aryl maleimides; these authors discussed the hindered *N*-aryl rotations (but not the bridgehead phenyl rotations) with some NMR data and x-ray structures.

There has clearly been substantial interest and experimental work with the phencyclone adducts and *N*-aryl maleimides, especially with fluorinated systems, and the fluorine-containing compounds are particularly important for biomedical applications (11). We have therefore undertaken an extensive computational study of hindered rotations in some relevant model compounds.

These molecular modeling calculations have employed semiempirical and *ab initio* techniques (12). Presented here are detailed results for *N*-aryl rotation

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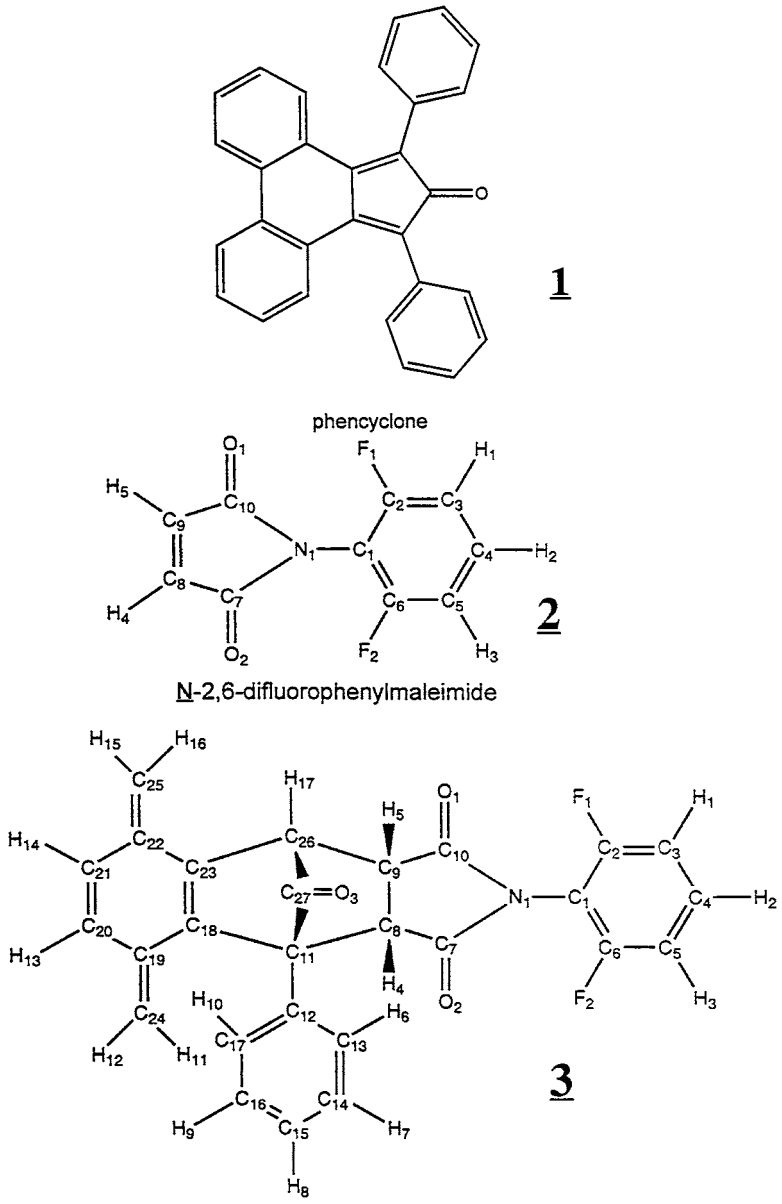

Figure 1. Structures and atom numbering for compound 2, *N*-2,6–difluorophenyl-maleimide, and for compound 3, a *simplifield model* for the Diels-Alder adduct of 2 with phencyclone, 1.

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in *N*-2,6-difluorophenylmaleimide, 2, as well as studies of the bridgehead phenyl rotation and the *N*-2,6-difluorophenyl rotation in compound 3, selected as a simplified model for the adducts of phencyclone. Thus, these calculations directly bear on both the $C(sp^2)$-$C(sp^3)$ bridgehead phenyl rotation and the N–C(aryl) rotation in the phencyclone adducts and maleimide precursors.

METHODS

Quantum chemical calculations (ab initio) are applied to the study of two compounds. *N*-2,6-Difluorophenylmaleimide, 2, was chosen as the Diels-Alder dienophile component, with two fluorine atoms providing *ortho, otho*' disubstitution on the NB-aryl ring. Compound 3 was designed as a simplified, truncated model for Diels-alder adducts of 1, in which one (bridgehead) phenyl is replaced by hydrogen, and the phenanthrenoid moiety from 1 is reduced to a 1,4-*bis*-methylenecyclohenadienoid moiety. The atom numbering for this work is shown in Figure 1 for compounds 2 and 3.

The calculations are at Hartree-Fock level, using the 3-21G and the 6-31G* basis sets, as implemented by the MacSpartan and PC Spartan (12) computer programs. Compound 2 is investigated from the point of view of the steric hindrance due to the proximity of the fluorines and the respective oxygen atoms, upon the rotation of the difluorobenzene ring around the N1−C1 bond. The dihedral angle C10N1C1C2 (called angle alpha) is set at an initial value of 90° and all the parameters of the molecule are optimized at both 3-21G and 6-31G* levels. In addition, the angle is frozen at values of 0°, 45°, 95°, 120° and 180° and the rest of the molecule's parameters are optimized. The energies thus obtained are shown in Table 1. The optimized values of the geometrical parameters are shown in Table 2.

Compound 3 is investigated from the point of view of the steric hindrance due to the proximity of H6 and O2, H6 and H4 and H10 and H11 upon the rotation of the phenyl ring around the C11-C12 bond. The angle chosen to characterize the rotation is the dihedral angle C27C11C12C17 (called angle beta). Through the rotation, the

Table 1. Energies (au) of Compound 2—6-31G* and 3-21G

	6-31G*	3-21G
0°	−784.6213565	−780.2779024
45°	−784.6445845	−780.3043546
95°	−784.6473331	−780.3057369
20°	−784.6468209	−780.3063063
180°	−784.6181358	−780.2756286
Optimized	−784.6473604	−780.3063906

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Table 2. Compound 2 Geometric Parameters—6-31G* Distances in Angstroms; Angles in Degrees

	0°	45°	79°	95°	120°	180°
Bond						
N1-C1	1.433	1.412	1.409	1.409	1.409	1.436
F1-C2	1.321	1.321	1.321	1.321	1.320	1.322
F2-C6	1.320	1.320	1.321	1.321	1.321	1.321
O1-C10	1.181	1.183	1.183	1.183	1.183	1.181
O2-C7	1.181	1.183	1.183	1.183	1.183	1.181
C1-C2	1.389	1.384	1.383	1.383	1.383	1.395
C2-C3	1.381	1.378	1.377	1.377	1.377	1.376
C3-C4	1.378	1.383	1.385	1.385	1.384	1.381
C4-C5	1.383	1.385	1.385	1.385	1.385	1.379
C5-C6	1.374	1.376	1.377	1.377	1.377	1.379
C6-C1	1.399	1.385	1.383	1.383	1.384	1.394
N1-C7	1.425	1.397	1.391	1.391	1.393	1.428
C7-C8	1.488	1.496	1.498	1.498	1.497	1.487
C8-C9	1.314	1.318	1.318	1.318	1.318	1.313
C9-C10	1.490	1.497	1.498	1.498	1.497	1.487
C10-N1	1.417	1.396	1.391	1.391	1.392	1.421
Bond Angle						
C1C2C3	123.015	122.325	122.291	122.287	122.287	123.741
C2C3C4	119.615	118.701	118.395	118.381	118.514	119.188
C3C4C5	119.730	120.851	121.174	121.197	121.041	119.617
C4C5C6	118.786	118.558	118.395	118.378	118.468	119.413
C5C6C1	123.735	122.452	122.290	122.286	122.332	123.310
F1C2C3	116.461	119.016	119.497	119.498	119.395	117.021
F1C2C1	120.086	118.626	118.212	118.216	118.316	118.660
F2C6C1	118.862	118.321	118.213	118.201	118.251	120.410
F2C6C5	117.348	119.226	119.497	119.513	119.417	116.246
C6C1N1	116.550	120.388	121.276	121.249	121.490	123.795
C2C1N1	125.978	122.349	121.271	121.280	121.128	119.170
C1N1C7	115.508	122.954	124.550	124.546	124.192	115.756
C1N1C10	125.811	124.834	124.552	124.547	124.662	124.561
N1C7C8	107.403	105.889	105.588	105.585	105.637	107.559
C7C8C9	108.183	108.846	108.963	108.961	108.956	108.252
C8C9C10	109.124	109.065	108.962	108.963	108.987	108.934
C9C10N1	107.309	105.779	105.589	105.585	105.636	107.786
O1C10N1	126.605	126.388	126.201	126.202	126.239	126.205
O1C10C9	125.767	127.812	128.210	128.213	128.122	125.603
O2C7N1	126.285	126.073	126.199	126.187	126.180	126.930
O2C7C8	126.152	128.028	128.212	128.228	128.180	125.298
C10N1C7	105.958	110.151	110.897	110.907	110.728	105.322
C2C1C6	114.380	117.074	117.454	117.470	117.339	114.315

(*continued*)

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Table 2. *Continued*

	0°	45°	79°	95°	120°	180°
Dihedral Angle						
C1C2C3C4	3.627	−0.152	−0.369	0.217	0.328	−2.188
C2C3C4C5	1.066	0.439	0.178	−0.090	−0.517	−0.548
F1C2C3C4	176.017	177.738	179.686	−179.860	−179.210	−173.338
F2C6C5C4	171.010	177.524	179.687	−179.880	−178.410	−172.228
F1C2C1N1	19.728	5.895	0.138	0.059	−2.099	−20.846
F2C6C1N1	−5.620	−2.161	0.130	−0.146	0.587	8.862
C7C8C9C10	3.877	1.091	0.157	−0.081	−0.536	−4.935
O1C10C9C8	179.047	−179.420	179.720	−179.810	179.621	−177.475
O2C7C8C9	163.975	174.939	179.720	−179.900	−177.590	−162.363
C9C8C7N1	−11.642	−3.956	−0.129	0.021	1.825	12.645
C8C9C10N1	5.203	2.157	−0.130	0.112	−0.943	−4.430
C7N1C1C6	65.317	68.101	79.060	95.380	109.769	113.390
C4C5C6C1	−6.258	−2.099	−0.372	0.132	1.399	5.637
Interatom. Dis.						
O1 F1	2.556	2.836	3.461	3.855	4.327	4.924
O2 F2	2.593	2.992	3.461	3.859	4.226	4.513
O1 F2	4.799	4.484	3.989	3.606	3.073	2.543
O2 F1	4.654	4.359	3.989	3.605	3.134	2.533

difluorobenzene ring is allowed to optimize; it adopts the same conformation as in the totally optimized Compound 2. Except for the optimized value, the angle beta is frozen at values of 0°, 30°, 60°, 90°, 120°, 150° and 180°, and all the other parameters of the molecule are allowed to optimize. These calculations were performed using the 3-21G basis set. Indeed, the size of the system would make it difficult to use a set as large as 6-31G*. When comparisons were made between the 3-21G and the 6-31G* results for compound 2, the relative energies of conformations with different values of alpha were found in good agreement. The energies thus obtained are shown in Table 3 and the optimized parameters are shown in Table 4.

RESULTS AND DISCUSSION

Examining Table 1, it can be seen that, at HF/6-31G* level, the most stable conformation of compound 2 (*N*-2,6-difluorophenylmaleimide) features the dihedral angle C10N1C1C2, called angle alpha, of 79°, with a shallow minimum around the stationary point. Indeed, at a value of 95° for alpha, the energy rises by only 0.02 kcal/mol. It can thus be seen that in the most stable state the difluorobenzene ring is quasi-perpendicular to the five-membered ring, insuring the largest

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distances between the fluorines and the oxygens. These distances are 3.461 Å for O1-F1 and for O2-F2, and 3.989 Å for 01-F2 and 02-F1, at the optimized structure, and feature similar values for the 95° value of alpha. The least stable conformations of compound 2, as expected, feature angles alpha of 0° and 180°. The 180° value is higher in energy than the stationary point by 18.34 kcal/mol, followed by the 0° value, higher than the stationary point by 16.32 kcal/mol. Since the system is seemingly symmetric, this difference might be questioned. However, when alpha is set at a 0° value, it does not necessarily follow that the C2C1N1C7 angle will adopt a 180° value; this depends on planarity at nitrogen.

At HF/3-21G calculational level, the lowest energy is obtained for a value of 64.92° for the angle alpha. This value differs from the preceding but the energy minimum is also very shallow. Between this value of alpha and the value of 75° there is only a difference of 0.17 kcal/mol. The highest energy is obtained for á = 180° in agreement with the 6-31G* results. This energy is higher than the lowest energy by 19.3 kcal/mol, a value quite close to the 6-31G* result. As such, the calculations using the 3-21G basis set, performed for the larger compound 3, can be deemed reliable.

In those conformations where there is strong steric hindrance between the fluorines and the oxygens, the geometry of the molecules is altered in such a way as to relieve as much of the hindrance as possible. These changes can be seen in bond lengths, bond angles and dihedral angles. For example, in Table 2, one sees that the N1−C1 bond is the longest for the least stable conformation (á = 180°) and very slightly shorter for á = O° while the optimized structure and the á = 95° structure feature a shorter value, of 1.409 Å that is 2% shorter than the longest value of 1.436 Å. The N1−C7 and the N1−C10 bonds have average values of 1.421 Å for á = O° and 1.391 Å for the most stable conformation, also a 2% effect. On the other hand, the C=O bonds show a .002 Å shortening for the hindered structures. These effects try to maximize the F–O distance in the hindered structures.

Table 3. Energies (au) of Compound 3—3-21G

	3-21G
0°	−1501.849942
30°	−1501.855422
38.996°	−1501.855835
60°	−1501.853264
90°	−1501.845217
120°	−1501.83931
150°	−1501.833158
180°	−1501.848594

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Table 4. Compound 3 Geometric Parameters—3-21G Distances in Angstroms; Angles in Degrees

	0°	30°	38.996°	60°	90°	120°	150°	180°
Bond								
N1-C1	1.407	1.407	1.407	1.407	1.407	1.408	1.407	1.407
F1-C2	1.350	1.350	1.350	1.351	1.351	1.351	1.350	1.350
F2-C6	1.347	1.347	1.347	1.347	1.347	1.347	1.347	1.347
O1-C10	1.202	1.201	1.201	1.201	1.201	1.201	1.202	1.202
O2-C7	1.204	1.205	1.205	1.204	1.202	1.202	1.201	1.202
C1-C2	1.377	1.376	1.377	1.377	1.377	1.377	1.377	1.377
C2-C3	1.372	1.372	1.372	1.372	1.372	1.371	1.372	1.372
C3-C4	1.382	1.382	1.382	1.383	1.383	1.383	1.382	1.382
C4-C5	1.382	1.382	1.382	1.381	1.381	1.381	1.381	1.382
C5-C6	1.374	1.373	1.373	1.374	1.374	1.374	1.374	1.374
C6-C1	1.376	1.376	1.376	1.376	1.376	1.376	1.376	1.376
N1-C7	1.390	1.388	1.388	1.390	1.393	1.393	1.394	1.390
C7-C8	1.522	1.518	1.516	1.512	1.514	1.514	1.515	1.521
C8-C9	1.547	1.551	1.552	1.551	1.552	1.552	1.540	1.546
C9-C10	1.508	1.509	1.510	1.512	1.511	1.510	1.512	1.508
C10-N1	1.390	1.392	1.392	1.394	1.392	1.392	1.392	1.390
C8-C11	1.573	1.574	1.572	1.571	1.573	1.578	1.562	1.572
C11-C12	1.519	1.512	1.509	1.504	1.511	1.515	1.512	1.517
C12-C13	1.395	1.391	1.390	1.386	1.388	1.394	1.392	1.389
C13-C14	1.381	1.383	1.384	1.387	1.384	1.379	1.383	1.386
C14-C15	1.385	1.383	1.383	1.381	1.382	1.385	1.383	1.380
C15-C16	1.380	1.382	1.383	1.386	1.383	1.379	1.382	1.385
C16-C17	1.387	1.384	1.383	1.380	1.382	1.386	1.384	1.381

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C17-C12	1.389	1.390	1.390	1.391	1.390	1.385	1.387	1.393
C11-C18	1.560	1.546	1.540	1.531	1.535	1.542	1.574	1.564
C18-C19	1.473	1.468	1.467	1.466	1.470	1.475	1.481	1.474
C19-C24	1.328	1.328	1.328	1.328	1.328	1.327	1.328	1.328
C19-C20	1.477	1.476	1.475	1.475	1.475	1.478	1.481	1.478
C20-C21	1.324	1.325	1.325	1.326	1.325	1.324	1.322	1.323
C21-C22	1.468	1.471	1.471	1.473	1.473	1.472	1.469	1.468
C22-C25	1.329	1.328	1.328	1.328	1.328	1.328	1.328	1.329
C22-C23	1.461	1.461	1.461	1.461	1.462	1.463	1.463	1.461
C23-C18	1.342	1.340	1.340	1.339	1.339	1.341	1.344	1.343
C23-C26	1.516	1.517	1.517	1.517	1.516	1.514	1.515	1.516
C26-C9	1.548	1.551	1.552	1.555	1.558	1.559	1.547	1.547
C26-C27	1.532	1.531	1.532	1.535	1.530	1.525	1.543	1.533
C27-C11	1.560	1.560	1.560	1.558	1.558	1.561	1.556	1.559
C27-O3	1.199	1.197	1.196	1.195	1.194	1.195	1.197	1.199
Dihedral Angle								
C10N1C1C2	65.586	64.798	64.663	64.703	65.400	65.295	64.582	65.460
C1C2C3C4	−0.786	−0.794	−0.794	−0.776	−0.779	−0.782	−0.841	−0.795
C2C3C4C5	0.338	0.133	0.304	0.304	0.350	0.370	0.320	0.338
F1C2C3C4	179.294	179.272	179.290	179.320	179.358	179.425	179.168	179.277
F2C6C5C4	179.434	179.568	179.584	179.564	179.440	179.436	179.383	179.421
F1C2C1N1	0.373	0.492	0.469	0.274	0.167	0.028	0.230	0.349
F2C6C1N1	0.163	−0.066	−0.074	0.152	0.318	0.382	0.456	0.214
C7C8C9C10	−5.694	−0.706	0.826	2.859	0.123	0.227	−6.388	−6.120
O1C10C9C8	−177.740	179.446	178.557	177.320	178.712	178.316	−177.160	−177.440

(*continued*)

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Table 4. *Continued*

	0°	30°	38.996°	60°	90°	120°	150°	180°
Dihedral Angle								
O2C7C8C9	−175.650	178.995	177.677	176.684	179.893	179.927	−173.790	−175.040
C9C8C7N1	6.294	1.428	0.097	−1.375	1.685	1.823	7.310	6.770
C8C9C10N1	3.207	−0.245	−1.470	−3.377	−1.891	−2.200	3.305	3.437
C7N1C1C6	64.635	65.967	65.233	65.940	66.709	67.022	63.923	64.533
C4C5C6C1	−0.719	−0.709	−0.706	−0.645	−0.695	−0.722	−0.728	−0.720
C7C8C9C26	112.643	117.925	119.709	122.478	120.088	120.156	112.087	112.251
C10C9C8C11	−126.650	−122.000	−120.460	−118.090	−120.560	−121.030	−126.510	−127.060
C8C9C26C27	40.986	37.795	36.633	34.675	36.222	36.616	39.951	41.121
C9C8C11C27	−26.715	−31.498	−33.260	−36.368	−34.449	−33.800	−26.451	−26.300
C9C26C27O3	122.900	122.177	121.996	121.215	119.378	118.545	124.297	122.921
C8C11C27O3	−129.060	−125.110	−123.770	−121.110	−120.360	−119.950	−130.350	−129.360
C12C17C16C15	1.384	0.364	−0.040	−0.988	−0.221	0.138	0.548	0.425
C17C16C15C14	0.882	0.077	−0.214	−0.648	0.189	0.764	−0.379	−0.241
C16C15C14C13	−0.785	−0.063	0.227	0.714	−0.201	−0.777	0.505	0.260
C18C11C12C17	−115.290	−84.957	−75.984	−55.743	−25.508	2.898	34.851	64.865
C27C11C12C17	0.089	30.000	38.996	60.000	90.000	120.000	150.000	−179.870
C11C12C17H10	5.860	−1.030	−1.649	−1.915	2.294	−1.213	5.809	3.477
C15C16C17H10	−179.440	−178.320	−178.820	179.888	−179.800	−178.430	175.822	178.238
C11C18C23C26	−5.448	−1.862	−0.888	1.077	1.945	2.305	−8.633	−6.325
C11C18C19C24	6.922	−2.455	−4.119	−8.083	−12.309	−20.312	25.587	11.187
C18C19C20C21	−2.335	3.428	4.344	6.714	10.855	16.491	−16.318	−5.238
C19C20C21C22	0.990	0.636	0.585	0.370	0.225	−0.440	2.429	1.276
C18C19C24H11	−2.292	−0.638	−0.341	0.120	0.310	0.651	−5.080	−3.044
C20C19C24H11	−177.540	179.897	179.348	177.559	175.013	172.087	−172.570	−176.570

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C18C11C12C13	73.485	96.158	103.293	120.552	157.037	−175.870	−143.230	−113.170
C27C11C12C13	−171.120	−148.880	−141.720	−123.700	−87.454	−58.771	−28.084	2.086
C23C18C19C24	−170.890	177.354	175.198	169.781	161.585	152.084	−146.660	−165.720
C21C20C19C24	173.464	−177.040	−175.370	−170.980	−164.370	−155.860	152.667	169.050
Ineratomic Dist.								
O1 F1	3.035	3.024	3.024	3.032	3.048	3.053	3.009	3.031
O2 F2	2.984	3.022	3.038	3.066	3.069	3.074	2.968	2.980
H10 H11	4.094	3.812	3.690	3.373	2.781	2.281	2.239	2.476
H10 O3	2.140	2.316	2.454	2.935	3.768	4.402	4.932	5.060
H10 H4	3.852	4.304	4.400	4.573	4.706	4.527	3.785	3.124
H10 O2	5.610	5.658	5.619	5.423	4.893	4.292	2.811	2.223
H6 H11	2.459	2.679	2.797	3.164	4.132	4.880	4.505	4.032
H6 O3	5.051	4.888	4.795	4.509	3.672	2.780	2.389	2.148
H6 H4	2.997	2.594	2.488	2.232	1.991	2.197	3.051	3.827
H6 O2	2.180	2.197	2.263	2.536	3.703	4.466	5.173	5.588
Bond Angle								
C1C2C3	121.688	121.680	121.696	121.765	121.848	121.864	121.774	121.702
C2C3C4	118.896	118.900	118.895	118.870	118.841	118.841	118.898	118.895
C3C4C5	120.470	120.475	120.470	120.450	120.422	120.412	120.417	120.462
C4C5C6	119.155	119.141	119.148	119.185	119.240	119.247	119.205	119.164
C5C6C1	121.393	121.404	121.409	121.410	121.395	121.410	121.432	121.397
F1C2C3	120.047	120.057	120.056	120.037	120.023	120.028	119.980	120.040
F1C2C1	118.265	118.263	118.248	118.198	118.129	118.107	118.246	118.258
F2C6C1	118.709	118.660	118.667	118.771	118.911	118.963	118.798	118.729
F2C6C5	119.898	119.929	119.913	119.818	119.694	119.627	119.769	119.873
C6C1N1	121.364	121.266	121.305	121.533	121.843	121.988	121.609	121.417

(*continued*)

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Table 4. *Continued*

	0°	30°	38.996°	60°	90°	120°	150°	180°
Bond Angle								
C2C1N1	120.245	120.341	120.320	120.153	119.909	119.791	120.124	120.209
C1N1C7	122.732	122.761	122.805	122.870	122.913	122.963	122.871	122.773
C1N1C10	122.576	122.543	122.505	122.414	122.239	122.244	122.557	122.571
N1C7C8	107.672	107.840	107.781	107.508	107.284	107.400	107.165	107.599
C7C8C9	104.042	104.367	104.591	105.136	105.101	104.959	105.025	104.171
C8C9C10	106.137	105.857	105.661	105.235	105.358	105.467	105.551	106.055
C9C10N1	107.061	107.213	107.254	107.306	107.328	107.285	107.156	107.059
O1C10N1	124.932	124.841	124.797	124.707	124.793	124.827	124.863	124.912
O1C10C9	128.000	127.945	127.949	127.984	127.875	127.886	127.979	128.023
O2C7N1	123.531	123.892	124.149	124.682	124.525	124.363	124.518	123.671
O2C7C8	128.768	128.221	128.023	127.780	128.166	128.209	128.307	128.705
C10N1C7	114.686	114.696	114.689	114.703	114.833	114.767	114.571	114.651
C2C1C6	118.391	118.393	118.375	118.314	118.247	118.220	118.267	118.373
C7C8C11	114.641	115.004	114.966	114.500	114.316	114.859	113.200	114.496
C9C8C11	105.376	104.866	104.724	104.590	104.508	104.549	106.082	105.548
C26C9C8	103.197	103.864	104.003	104.109	104.199	104.220	102.775	103.037
C10C9C26	112.363	112.459	112.703	113.479	113.701	113.617	112.872	112.488
C8C11C12	114.374	116.601	117.044	117.487	118.743	116.241	111.695	113.970
C8C11C18	105.299	105.898	106.273	106.684	104.880	104.735	106.405	105.479
C8C11C27	99.204	97.811	97.303	96.159	96.523	96.384	100.341	99.424
C11C12C13	119.489	120.781	121.438	122.592	121.762	117.886	119.103	121.433
C11C12C17	121.443	120.396	119.623	118.376	119.835	124.018	122.257	119.755
C12C13C14	120.652	120.500	120.406	120.355	120.848	121.148	120.680	120.389
C13C14C15	120.372	120.352	120.340	120.314	120.289	120.167	120.246	120.493
C14C15C16	119.341	119.456	119.530	119.606	119.374	119.260	119.442	119.423

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C15C16C17	120.532	120.433	120.322	120.121	120.228	120.517	120.395	120.361
C16C17C12	120.492	120.439	120.465	120.623	120.844	120.811	120.615	120.546
C11C18C19	131.670	130.323	129.928	129.348	129.957	131.561	133.931	132.194
C11C18C23	107.424	108.072	108.234	108.490	108.358	107.963	106.846	107.198
C18C19C24	126.245	125.539	125.244	124.690	124.622	125.216	126.294	126.399
C18C19C20	114.254	114.115	114.054	113.942	113.927	113.808	114.029	114.254
C18C23C25	109.804	109.555	109.456	109.303	109.472	109.856	109.779	109.874
C18C23C22	124.500	124.058	123.870	123.52 7	123.551	123.807	124.573	124.592
C19C20C21	123.952	123.676	123.542	123.262	123.058	122.752	123.121	123.940
C20C21C22	122.098	122.286	122.372	122.486	122.268	121.824	121.782	122.036
C21C22C23	114.105	113.981	113.960	113.941	114.014	113.970	114.271	114.153
C21C22C25	122.483	122.465	122.437	122.398	122.384	122.487	122.324	122.446
C25C22C23	123.378	123.538	123.590	123.655	123.597	123.541	123.317	123.357
C22C23C26	125.678	126.384	126.674	127.164	126.954	126.334	125.643	125.519
C23C26C9	108.792	107.860	107.503	106.859	106.693	107.091	108.353	108.816
C23C26C27	96.815	97.300	97.465	97.865	98.188	98.023	96.242	96.712
C23C18C19	120.878	121.605	121.835	122.134	121.460	120.132	118.878	120.552
C26C27C11	97.696	97.729	97.652	97.520	97.894	98.156	97.177	97.623
C26C27O3	130.033	130.917	131.408	131.977	131.912	131.720	131.171	130.121
C11C27O3	132.261	131.352	130.939	130.503	130.173	130.079	131.649	132.250
C17C12C13	118.499	118.814	118.935	118.931	118.356	118.085	118.613	118.783
C24C19C20	119.349	120.345	120.701	121.324	121.263	120.484	118.620	119.065
C9C26C27	98.962	98.547	98.384	97.980	97.514	97.500	100.176	99.152
C27C11C12	118.916	117.013	116.218	115.012	112.545	111.808	119.687	119.287
C12C11C18	121.202	119.848	119.689	119.819	121.567	127.887	122.789	121.247
C27C11C18	94.043	95.738	96.333	97.541	97.942	97.729	92.417	93.692

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The F1C2C3 angle increases by as much as 3.0° from the á = 0° to the optimized structure, while the F2C6C5 angle increases by 3.3° from á = 180° to á = 95°. While the angle C1N1C10 remains nearly constant through the rotation, the angle C1N1C7 decreases by 9° from the optimized structure to the hindered ones. The OCN angles remain fairly constant. The C7N1C10 angle decreases from the non-hindered structures to the hindered ones by about 5°. It is interesting to follow how hindrance introduces a slight puckering in the benzene ring. The hindered structures also show the respective oxygens moving out of the C7C8C9 plane by as much as 15°.

A particularly interesting variation is seen for the angle C7N1C1C6 which illustrates the play between sp^2 and sp^3 character of the *N* atom. In non-hindered conformations, the nitrogen is co-planar with the C7, C8, C9 and C10 atoms and exhibits sp^2 character, with N1–C1, N1–C10 and N1–C7 bonds co-planar, thus insuring for the C7N1C1C6 angle similar values as for the angle alpha. In the hindered conformations, the more hindered they are, the more out-of-plane N1 becomes and its sp^3 character increases, making the angle C7N1C1C6 quite different from the angle alpha. That is, the nitrogen becomes appreciably pyramidalized.

As far as the compound 3 is concerned, the optimized beta angle is 39°, the least stable conformation features a beta angle of 150°, higher in energy than the optimized value by 14.23 kcal/mol. (The angle beta is the dihedral angle C27C11C12C17.) In the least stable conformation, the H10-H11 distance is 2.239 Å, evidently producing high steric repulsion. The stability with beta equal to 39° could be due to several factors: a reasonable H10-H11 distance, a H6-H4 distance greater than the 90° and 120° value, and a possibility of hydrogen bond formation between 02 and H6.

It is conceivable that the H10-03, H6-03 and H6-02 interactions can contribute to the stabilization of the conformations which feature some of these distances around 2 Å. Indeed, the oxygens are negatively charged (in the vicinity of −0.5 eu) while the hydrogens exhibit positive charges between 0.1 and 0.2 eu. As such, an electrostatic attraction can occur. Since the hydrogens are on carbons and not on electronegative atoms, this effect might not be a "traditional" hydrogen bond, but it still may stabilize the system. (This kind of hydrogen bonding is now well accepted.) (13).

CONCLUSIONS

In general, it can be concluded that the rotation of the aromatic rings for both compounds investigated affects significantly the rest of the molecule and the structure of the rings themselves. At the cost of decreasing the *p* orbital overlap and the delocalization of the pi electrons, the geometries are modified in a way as to relieve somewhat the hindrance. Indeed, the special significance of this work lies,

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in part, in the elucidation of the considerable complexity of the distortions from planarity as the transition states are approached for the relevant bond rotations. In these models there is considerable flexing of moieties (aryl rings or five-membered ring imides) which are normally considered quite flat. The common conceptualization of "biaryl-type" rotations about the central bond, in which the two aryl rings each preserve their separate planarity as they rotate past one another through a totally planar transition state, is evidently quite simplistic. Such a picture would require maximal non-bonded steric repulsion of two *ortho-ortho*' pairs of atoms simultaneously (i.e. the 2-2′ and the 6-6′), using the numbering of the parent compound, biphenyl). Instead, the two aryl moieties pass one another with only one set of non-bonded proximal atoms, e.g., 2 and 2′ achieving minimum distance, while the distortions produced elongate somewhat the 6-6′ distance. As mentioned before, these distortions include deformation from planarity, pyramidalization of some atoms, bond stretching and bending. These complex synchronous motions thus serve to lower the energy barrier for rotating one moiety past the other.

These detailed results for hindered aryl rotations might provide insight for potential "molecular motors," for atropisomers and NMR studies of hindered molecules, and are of critical importance for studies of the crowded systems related to phenycclone Diels-Alder adducts.

ACKNOWLEDGMENTS

Partial support has been provided by the U.S. Education Department Minority Science Improvement Program (MSIP), National Science Foundation Instrumentation and Laboratory Improvement Program, and the Professional Staff Congress-City University of New York Research Award Program.

REFERENCES

1. Kelly, T.R.; De Silva, H.; Silva, R.A. Unidirectional Rotary Motion in a Molecular System. Nature **1999**, *401*, 150–152.
2. Koumura, N.; Zijlstra, R.W.J.; Van Delden, R.A.; Harada, N.; Feringa, B.L. Light-Driven Monodirectional Molecular Motor. Nature **1999**, *401*, 152–155.
3. (a) Abrahams, J.P.; Leslie, A.G.W.; Lutter, R.; Walker, J.E. Structure at 2.8 A Resolution of F_1-ATPase from Bovine Heart Mitochondria. Nature **1994**, *370*, 621–628.
   (b) Dominguez, R.; Freyzon, Y.; Trybus, K.M.; Cohen, C. Crystal Structure of a Vertebrate Smooth Muscle Myosin Domain and its Complex with the Essential Light Chain: Visualization of the Pre-Power Stroke State. Cell **1998**, *94*, 559–571.

(c) Block, S.M. Real Engines of Creation. Nature **1997**, *386*, 217–219.
(d) Boyer, P.D. The ATP Synthase-a Splendid Molecular Machine. Annu. Rev. Biochem. **1997**, *66*, 717–749.
(e) Shingyoji, C.; Higuchi, H.; Yoshimura, M.; Katayama, E.; Yanagida, T. Dynein Arms are Oscillating Force Generators. Nature **1998**, *393*, 711–714.

4. Eguchi, T.; Kondo, K.; Kakinuma, K.; Uekusa, H.; Ohashi, Y.; Mizoue, K.; Qiao, Y.-F. Unique Solvent-Dependent Atropisomerism of a Novel Cytotoxic Naphthoxanthene Antibiotic FD-594. J. Org. Chem. **1999**, *64* (15), 5371–5376.
5. Monovich, L.G.; Le Huérou, Y.; Rönn, M.; Molander, G.A. Total Synthesis of (-)-Steganone Utilizing a Samarium (II) Iodide Promoted 8-endo ketyl-olefin Cyclization. J. Am. Chem. Soc. **2000**, *122* (1), 52–57.
6. (a) LaPlanche, L.A.; Xu, Y.; Benshafrut, R.; Rothchild, R.; Harrison, E.A., Jr. NMR Studies of Hindered Rotation of Unsubstituted Bridgehead Phenyl Rings in the Phencyclone-Norbornadiene Adduct. Spectrosc. Lett. **1993**, *26* (1), 79–101.
(b) Xu, Y.; LaPlanche, L.A.; Rothchild, R. Assignment of ^{13}C Resonances in the Phencyclone-Norbornadiene Adduct Via 2D NMR. ^{13}C Evidence for Hindered Rotation of Unsubstituted Bridgehead Phenyl Rings. Spectrosc. Lett. **1993**, *26* (1), 179–196.
(c) Callahan, R.; Rothchild, R.; Wyss, H. NMR. Studies of Hindered Rotation. The Diels-Alder Adduct of Phencyclone with *p*-Benzoquinone: Restricted Motion of Bridgehead Phenyls. Spectrosc. Lett. **1993**, *26* (9), 1681–1693.
(d) Benshafrut, R.; Callahan, R.; Rothchild, R.; NMR Studies of Hindered Rotation. The Diels-Alder Adduct of Phencyclone with Maleic Anhydride: Restricted Motion of Bridgehead Phenyls. Spectrosc. Lett. **1993**, *26* (10), 1875–1888.
(e) Bynum, K.; Rothchild, R. NMR Studies of Hindered Rotation. The Diels-Alder Adduct of Phencyclone with *N*-*n*-Propylmaleimide: Restricted Motion of Bridgehead Phenyls. Spectrosc. Lett. **1996**, *29* (8), 1599–1619.
(f) Bynum, K.; Rothchild, R. NMR Studies of Hindered Rotation. The Diels-Alder Adduct of *N*-*n*-Butylmaleimide with Phencyclone: Restricted Motion of Bridgehead Phenyls. Spectrosc. Lett. **1996**, *29* (8), 1621–1634.
(g) Boccia, G.; Callahan, R.; Prip, R.; Rothchild, R. Studies of Hindered Rotation and Magnetic Anisotropy by ^{1}H, ^{19}F and ^{13}C NMR in Models for Drugs. The Diels-Alder Adduct of Phencyclone with *N*-2,2,2-Trifluoroethylmaleimide, and Precursors. Spectrosc. Lett. **1998**, *31* (7), 1367–1378.
(h) Bynum, K.; Rothchild, R.; Shariff, N. ^{1}H, ^{13}C and ^{19}F NMR Studies of the Diels-Alder Adduct of *p*-fluoranil with Phencyclone. Hindered Phenyl Rotations and Anisotropic Effects in a Model Compound for Drugs. Spectrosc. Lett. **1998**, *31* (7), 1379–1394.

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270 Madison Avenue, New York, New York 10016

7. (a) Amin, M.F.; Bynum, K.; Callahan, R.; Prip, R.; Rothchild, R. Studies of Hindered Rotation and Magnetic Anisotropy by ^{1}H, ^{13}C and ^{19}F NMR. The Diels-Alder Adduct of *N*-pentafluorophenylmaleimide and Phencyclone: A Model for Drugs. Spectrosc. Lett. **1998**, *31* (3), 673–692.
(b) Bynum, K.; Prip, R.; Callahan, R.; Rothchild, R. ^{19}F NMR Studies of the Diels-Alder Adduct of *N*-pentafluorophenylmaleimide with Phencyclone. Hindered Rotation About a N–C_6F_5 bond. J. Fluorine Chem. **1998**, *90* (1), 39–46.
8. (a) Azaryayev, N.; Callahan, R.; Rothchild, R. Multinuclear NMR Studies of Hindered Rotations in Phencyclone Diels-Alder Adducts with Maleimides. Paper no. 261, Eastern Analytical Symposium, Nov. 14–19, 1999 (Somerset NJ).
(b) Sklyut, O.; Callahan, R.; Rothchild, R. Hindered Rotation in a Diels-Alder Adduct of Phencyclone with *N*-2,3,5,6-tetrafluorophenyl Maleimide. Paper no. 262, Eastern Analytical Symposium, Nov. 14–19, 1999 (Somerset NJ).
9. Curran, D.P.; Qi, H.; Geib, S.J.; DeMello, N.C. Atroposelective Thermal Reactions of Axially Twisted Amides and Imides. J. Org. Chem. **1994**, *116* (7), 3131–3132.
10. Eto, M.; Setoguchi, K.; Harada, K.; Sugiyama, E.; Harano, K. Phenycyclone Diels-Alder Adducts as a New Crystalline Host. Role of CH–g and CH–O Interactions. Tetrahedron Lett. **1998**, *39*, 9751–9754.
11. Filler, R.; Kobayashi, Y.; Yagupolskii, L.M. Eds. *Organofluorine Compounds in Medicinal Chemistry and Biomedical Applications*. New York: Elsevier, 1993.
12. Wavefunction Inc. (Irvine CA), *PC Spartan and MacSpartan* Molecular Modeling Computer Programs, 1996.
13. Jeffrey, G.A. *An Introduction to Hydrogen Bonding*. New York: Oxford University Press, 1997. Chapt. 5 (pp. 79–97, esp. p. 93).

Received June 1, 2000
Accepted December 10, 2000

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