

## How Do Different Fluorine Substitution Patterns Affect the Electronic State Energies of Phenylnitrene?

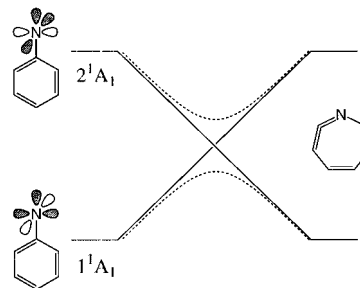
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Substituted phenylnitrenes, reacting out of their closed-shell-singlet (CSS) states, can serve as photoaffinity labeling reagents if they engage in bond insertion reactions.<sup>1–3</sup> Such reactivity is similar to that exhibited by singlet phenylcarbene.<sup>4</sup> However, the reactivity of unsubstituted CSS phenylnitrene (PhN) is dominated by unimolecular ring expansion to form dihydroazepine.<sup>4,5</sup> Substituents on the aromatic ring are required for bimolecular insertion reactions to compete with ring expansion, e.g., polyfluorinated phenylnitrenes, which were first examined by Banks and Prakash.<sup>6,7</sup> Platz has demonstrated that the barrier to ring expansion in 2,6-difluorophenylnitrene (*o,o*-F<sub>2</sub>PhN) is increased by 3–5 kcal/mol compared to unsubstituted PhN.<sup>4,8</sup> Platz has also shown that proper location of the fluorines on the aromatic ring is critical to this effect; 3,5-difluorophenylnitrene (*m,m*-F<sub>2</sub>PhN), like PhN, undergoes ring expansion faster than it participates in insertion reactions.<sup>2–4</sup>

Elucidating the energies for different electronic states of PhN has been the goal of several experimental<sup>9,10</sup> and theoretical<sup>11–13</sup> studies. Theory and experiment are in good agreement on the relative ordering of the lowest energy states. The ground state is a triplet (<sup>3</sup>A<sub>2</sub>), the first excited state is an open-shell singlet (<sup>1</sup>A<sub>2</sub>) lying about 18 kcal/mol higher in energy, and higher still is the first CSS (<sup>1</sup>A<sub>1</sub>). No experimental number is available for the relative energy of the latter state, but reasonable quality single- and multireference configuration interaction (CISD+Q) calculations place it 31–39 kcal/mol above the triplet. The electronic configuration of this state is dominated by double occupation of the nitrogen p orbital that lies in the plane of the aromatic ring. The next higher lying CSS (<sup>2</sup>A<sub>1</sub>) is derived from double excitation of that pair of electrons out of the in-plane p orbital and into the aromatic π system. Kim et al.<sup>12</sup> have estimated the energy of this state to be about 52 kcal/mol above the triplet, but the errors associated with this calculation may be substantial (vide infra). The energy of this state bears on the ring expansion reactivity of PhN insofar as it correlates with the CSS ground state of dihydroazepine, i.e., the ring expansion is a Wagner–Meerwein shift of a C–C bond to the electron-deficient nitrogen using the empty in-plane p orbital. On the basis of this analysis, Platz has speculated that different fluorine substitution patterns may preferentially stabilize the



**Figure 1.** State correlation diagram for the ring expansion of phenylnitrene to dihydroazepine. Filled orbitals are shaded. The solid lines correlate the states diabatically; the curved lines are adiabatic paths generated by avoided crossing. This diagram is schematic in nature and is not intended to accurately represent state energies for either species.

<sup>1</sup>A<sub>1</sub> state and hence lead to higher activation barriers for ring expansion.<sup>4</sup> Of course, a more complete explanation includes the recognition that there must be an avoided crossing in the state–symmetry correlation diagrams, but the crux of the argument remains a differential effect on the relative energies of the two CSS states (Figure 1).

In order to address this question, we have employed density functional theory<sup>14</sup> (DFT) to calculate<sup>15,16</sup> the relative energies of the triplet and CSS states of PhN, (*o,o*-F<sub>2</sub>)PhN, (*m,m*-F<sub>2</sub>)PhN, and 4-fluorophenylnitrene (*p*-FPhN) and their corresponding dihydroazepines. To assess the quality of this level of theory, we have compared the DFT results for PhN to multi-reference second-order perturbation theory (CASPT2N)<sup>17,18</sup> employing an eight-electron/eight-orbital active space and also to single-reference coupled cluster<sup>19</sup> calculations including all single, double, and perturbative triple<sup>20</sup> excitations (CCSD(T)). These calculations are summarized in Table 1.

The gap between the <sup>3</sup>A<sub>2</sub> and <sup>1</sup>A<sub>1</sub> states for PhN appears to be well predicted by DFT. On the basis of the results for methylene, Roos has suggested that the CASPT2N level overstabilizes triplets relative to singlets by 3–5 kcal/mol.<sup>21</sup> Our own calculations for various carbenes and nitrenium ions have shown similar overstabilizations of triplet states by up to 8 kcal/mol.<sup>22</sup> The CCSD(T) calculations also support the DFT results. Because of the size of PhN, calculations at this level were not performed using a triple-ζ basis. The larger stabilization of the triplet at this level of theory compared to DFT is consistent with lesser flexibility in the basis set and the observed tendency of CCSD(T) to overstabilize triplets relative to CSSs by 1–2 kcal/mol in carbenes and nitrenium ions.<sup>22</sup> Similar levels of DFT have previously been shown to accurately predict singlet–

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**Table 1.** Relative Electronic State Energies (kcal/mol) for PhN, Didehydroazepine, and Fluoroderivatives

molecule	electronic state	BLYP <sup>a</sup>	CASPT2N <sup>b</sup>	CCSD(T) <sup>c</sup>
PhN	<sup>3</sup> A <sub>2</sub> <sup>d</sup>	0.0 (0.0)	0.0	0.0
	1 <sup>1</sup> A <sub>1</sub>	29.5 (29.6)	34.8	35.2
	2 <sup>1</sup> A <sub>1</sub>	41.0 (38.9)	54.5	47.2
<i>(o,o</i> -F <sub>2</sub> )PhN	didehydroazepine <sup>e</sup>	7.4 (7.2)		
	<sup>3</sup> A <sub>2</sub> <sup>f</sup>	0.0 (0.0)		
	1 <sup>1</sup> A <sub>1</sub>	23.5 (23.7)		
	2 <sup>1</sup> A <sub>1</sub>	48.5 (48.2)		
<i>(m,m</i> -F <sub>2</sub> )PhN	didehydroazepine <sup>e</sup>	4.9 (5.2)		
	<sup>3</sup> A <sub>2</sub> <sup>g</sup>	0.0 (0.0)		
	1 <sup>1</sup> A <sub>1</sub>	30.9 (31.0)		
	2 <sup>1</sup> A <sub>1</sub>	42.4 (42.7)		
<i>p</i> -FPhN	didehydroazepine <sup>e</sup>	5.7 (5.8)		
	<sup>3</sup> A <sub>2</sub> <sup>h</sup>	0.0 (0.0)		
	1 <sup>1</sup> A <sub>1</sub>	26.7 (26.7)		
	2 <sup>1</sup> A <sub>1</sub>	43.3 (43.3)		
	didehydroazepine <sup>e</sup>	7.8 (7.7)		

<sup>a</sup> BLYP/cc-pVTZ//BLYP/cc-pVDZ level. Energies in parentheses are corrected for zero-point vibrational energy. All states are local minima based on analysis of their analytic Hessian matrices. <sup>b</sup> CASPT2N/cc-pVTZ//CAS(8,8)/cc-pVDZ level. <sup>c</sup> CCSD(T)/cc-pVDZ//CAS(8,8)/cc-pVDZ level. <sup>d</sup> Absolute electronic energies (au) for this row are -286.293 23, -285.806 55, and -285.509 37. <sup>e</sup> Derived from ring expansion of the corresponding aromatic nitrene. <sup>f</sup> Absolute electronic energy (au) is -484.838 58. <sup>g</sup> Absolute electronic energy (au) is -484.843 20. <sup>h</sup> Absolute electronic energy (au) is -385.570 07.

triplet gaps in phenylcarbene and phenylnitrenium<sup>23</sup> and other hypovalent systems.<sup>24,25</sup>

Quantitative accuracy for the 2<sup>1</sup>A<sub>1</sub> state, on the other hand, is much harder to ascertain. The DFT energies are calculated from Kohn–Sham orbitals that would give rise to a Slater determinant corresponding to this state. No formal justification for such an analysis exists—to the extent that the Kohn–Sham orbitals resemble those calculated at the Hartree–Fock level (where it is also possible to converge the self-consistent-field equations to this excited-state determinant), this approach might be better viewed as calculating a DFT energy for an approximate HF density. Both the present CCSD(T) calculations and the above-noted CISD+Q calculations of Kim et al.<sup>12</sup> place this state considerably higher in energy than does DFT. However, those calculations used the excited state HF reference wave function. Since there is no guarantee that this wave function will be orthogonal to the ground state, the quality of those results is open to question (in addition, they used smaller basis sets that destabilize the CSS relative to the triplet). Finally, at the CASPT2N level the energy of the 2<sup>1</sup>A<sub>1</sub> state is higher still. It is possible that the standard stabilization of high-spin states over low-spin accounts for more than 10 kcal/mol in this instance, but additional work is required to confirm this.

On the basis of this analysis, DFT may be expected to provide good estimates of the <sup>3</sup>A<sub>2</sub> and 1<sup>1</sup>A<sub>1</sub> state energies in the fluorosubstituted systems, but not necessarily to provide quantitatively accurate energies for the 2<sup>1</sup>A<sub>1</sub> states. Nevertheless, we are confident that *trends* in the latter state's energy as a function of substitution will be well captured (the DFT results are quite consistent with observed trends in the HF energies, for instance). These trends are sufficient for the remainder of our discussion—more quantitative CASPT2N results will be reported in due course.

Table 1 indicates that fluorine substitution at the *ortho* or *para* positions stabilizes the 1<sup>1</sup>A<sub>1</sub> state and destabilizes the 2<sup>1</sup>A<sub>1</sub> state relative to the triplet. The magnitude of the increase in separation between the two CSSs in (*o,o*-F<sub>2</sub>)PhN (15.2 kcal/

mol including zero-point vibrational energy) is roughly double that for *p*-FPhN (7.3 kcal/mol). Fluorine substitution at the meta positions, on the other hand, results in only a very small increase in the energy separating the two CSSs, and in this case both are raised slightly in energy relative to the triplet by comparison to PhN. These results confirm Platz's hypothesis<sup>4</sup> on the nature and the regiodependence of the fluorine substitution effect. The calculated difference in relative stabilization for the *o,o*- and *p*-substituted systems (less for the latter) is consistent with the observed reactivity of these species.<sup>2</sup> The relative energies of the fluorinated didehydroazepines are uncorrelated with ring-expansion reactivity.

The origin of the stabilizing effect for the 1<sup>1</sup>A<sub>1</sub> state of the *o,o*- and *p*-substituted systems may be found in the electronic polarization of the aromatic  $\pi$  system. In all of the CSSs, negative  $\pi$ -charge density accumulates at the fluorine atoms and at the carbon atoms *ortho* and *para* to fluorine(s) on the ring.<sup>26</sup> In the *o,o*- and *p*-substituted 1<sup>1</sup>A<sub>1</sub> states, this places negative charge density adjacent to the (parallel) "empty" nitrogen p orbital and promotes formation of a partial double bond to the electron deficient nitrogen atom. This affects the C–N bond length: relative to 1<sup>1</sup>A<sub>1</sub> PhN, the C–N bond is 0.027 Å shorter in 1<sup>1</sup>A<sub>1</sub> *o,o*-F<sub>2</sub>PhN and 0.006 Å shorter in 1<sup>1</sup>A<sub>1</sub> *p*-FPhN (the triplet bond lengths change by less than 0.001 Å). For the 2<sup>1</sup>A<sub>1</sub> state, on the other hand, this polarization of the *o,o*- and *p*-substituted systems results in a repulsive interaction between densities localized on the N in this state and the *ipso* carbon. Again the C–N bond length reflects this interaction: relative to 2<sup>1</sup>A<sub>1</sub> PhN, the C–N bond is 0.025 Å longer in 2<sup>1</sup>A<sub>1</sub> *o,o*-F<sub>2</sub>-PhN and 0.009 Å longer in 2<sup>1</sup>A<sub>1</sub> *p*-FPhN. The polarization of the  $\pi$  system in these molecules is entirely consistent with the observed *ortho,para*-directing effect of fluorine substituents in electrophilic aromatic substitution reactions.<sup>27</sup>

As for *m,m*-F<sub>2</sub>PhN, it appears that the polarizing effects of the fluorine substituents and the nitrogen atom roughly cancel in all of the electronic states, so that no significant changes in state energies (or bond lengths) relative to PhN are observed. This is consistent with the similar reactivities observed for PhN and *m,m*-F<sub>2</sub>PhN.

Fluorine substitution at either the *ortho* or *para* positions of PhN polarizes the  $\pi$  system in a manner that stabilizes the 1<sup>1</sup>A<sub>1</sub> state and destabilizes the 2<sup>1</sup>A<sub>1</sub> state relative to the triplet. To the extent that 2<sup>1</sup>A<sub>1</sub> state character is reflected in the transition state for ring opening, this rationalizes the increased barrier for these substituted phenylnitrenes to engage in that process. This effect is absent for *meta*-substitution of fluorine. Further analysis will require characterization of the transition state structures for ring expansion.<sup>28</sup> In the latter case, we expect comparison to the recent phenylcarbene results of Matzinger et al.<sup>29</sup> will provide additional insights into critical differences in nitrene and carbene reactivities.

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**Supporting Information Available:** Cartesian coordinates for all nitrene and didehydroazepine local minima (6 pages). Ordering information is given on any current masthead page. Color maps of the electrostatic potential on an isodensity surface illustrating polarization of the aromatic  $\pi$  system for all species are available on the World Wide Web. See supporting information paragraph on any current masthead page for instructions on accessing the images.

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(26) Color maps of the electrostatic potential on an isodensity surface illustrate this polarization. These images are available as supporting information on the World Wide Web. See supporting information paragraph.

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