

Accurate Oxidation Potentials of 40 Benzene and Biphenyl Derivatives with Heteroatom Substituents

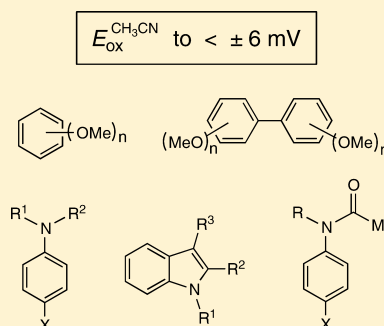
Pu Luo,[†] Adam M. Feinberg,[†] Gonzalo Guirado,^{*,‡} Samir Farid,^{*,†} and Joseph P. Dinnocenzo^{*,†}

[†]Department of Chemistry, University of Rochester, Rochester, New York 14627, United States

[‡]Departament de Química (Química-Física), Universitat Autònoma de Barcelona, Edifi C, 08193 Bellaterra, Barcelona, Spain

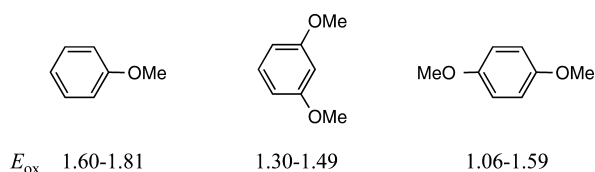
S Supporting Information

ABSTRACT: The redox equilibrium method was used to determine accurate oxidation potentials in acetonitrile for 40 heteroatom-substituted compounds. These include methoxy-substituted benzenes and biphenyls, aromatic amines, and substituted acetanilides. The redox equilibrium method allowed oxidation potentials to be determined with high precision ($\leq \pm 6$ mV). Whereas most of the relative oxidation potentials follow well-established chemical trends, interestingly, the oxidation potentials of substituted *N*-methylacetanilides were found to be higher than those of the corresponding acetanilides. Density functional theory calculations provided insight into the origin of these surprising results in terms of the preferred conformations of the amides versus their cation radicals.



INTRODUCTION

Our recent study¹ reexamining the Rehm–Weller data set² required accurate oxidation potentials for a number of methoxy-substituted benzenes in order to precisely define the functional relationship between the rate constant for electron transfer and the reaction driving force. The literature oxidation potentials determined electrochemically in acetonitrile for the electron donors used for that study were too uncertain to be reliably used. Consider, for example, the range in literature oxidation potentials (in V vs SCE) reported for the three methoxy-substituted benzenes shown below. In the endergonic region of the Rehm–Weller data set, where the rate constants for electron transfer decrease by 1 order of magnitude for every 0.059 eV increase in free energy of reaction, the oxidation potential ranges shown below lead to uncertainties in the predicted rate constants for electron transfer of ~ 3 – 9 orders of magnitude! Clearly, these uncertainties are unacceptably large to confidently test thermodynamic and kinetic relationships involving electron transfer reactions.



We describe herein the accurate determination of oxidation potentials in acetonitrile for the electron donors originally used in the Rehm–Weller work² by means of the redox equilibrium method described earlier.^{3,4} We also determined accurate oxidation potentials for a large number of other benzene and biphenyl derivatives with heteroatom substituents that should provide useful thermochemical data for a variety of purposes.

RESULTS AND DISCUSSION

The redox equilibrium method utilizes nanosecond transient absorption spectroscopy to determine the equilibrium constant for electron transfer between a reference compound of known oxidation potential (R) and a compound of unknown oxidation potential (C) (eq 1), from which the difference in oxidation potential can be determined (eq 2).



$$E_{ox}(R) - E_{ox}(C) = -RT \ln(K_{et}) \quad (2)$$

Although described in detail elsewhere,³ the method is briefly outlined here for clarity. *N*-Methylquinolinium hexafluorophosphate (NMQ⁺) in acetonitrile is used as a photooxidant and toluene (0.5 M) as a codonor. NMQ⁺ is excited at sufficiently long wavelength (343 nm) that there is no competitive absorption by the electron donors. The singlet excited state of NMQ⁺ is a powerful one-electron oxidant ($E_{red} = 2.6$ – 2.7 V vs SCE). Using toluene in high concentration as a codonor leads to the initial formation of the NMQ[•]/PhCH₃^{•+} geminate radical/cation-radical pair, which undergoes efficient separation. The “free” toluene cation radical is a powerful one-electron oxidant ($E_{red} = 2.26$ V vs SCE)^{3b} that effectively, irreversibly oxidizes the electron donors (R and C) that are present at relatively low concentration (e.g., ~ 1 – 20 mM) in solution. Thus, in a pulsed laser experiment, each laser pulse produces the same concentration of PhCH₃^{•+} and, consequently, the same total concentration of C^{•+} and R^{•+}. The reduced form of the photooxidant, NMQ[•], can be rapidly scavenged with dioxygen, leading to O₂^{•-}, which does not have interfering absorptions in

Received: July 31, 2014

Published: September 3, 2014

the UV–vis region where many organic cation radicals strongly absorb. Transient spectra are typically recorded at $\sim 1\text{--}2\ \mu\text{s}$ after the laser pulse, which allows time to establish the redox equilibrium before significant decay of the cation radicals.

Shown in Figure 1 is a representative example of transient redox equilibrium spectra from hexamethylbenzene and 1,3,5-

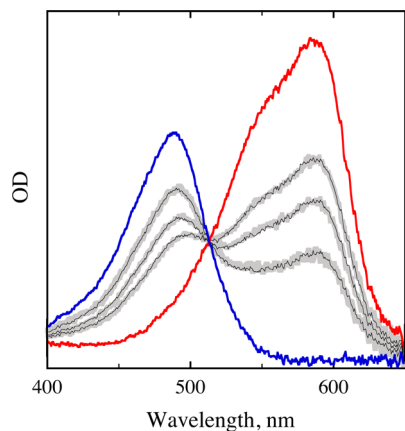


Figure 1. Transient spectra in acetonitrile at 20 °C for hexamethylbenzene cation radical (blue line), 1,3,5-trimethoxybenzene cation radical (red line), the redox equilibrium spectra (thick gray lines), and the best least-squares fits to the equilibrium spectra (thin black lines).

trimethoxybenzene. The spectrum for hexamethylbenzene^{•+} is shown in blue and that for 1,3,5-trimethoxybenzene^{•+} in red. The redox equilibrium spectra (thick gray lines) show a clean isosbestic point at $\sim 510\ \text{nm}$. Fitting of all of these spectra (thin black lines) as described previously^{3a} gives an average equilibrium constant of 0.205(8) at 20 °C, which corresponds to $\Delta G = +0.040(1)\ \text{eV}$ for eq 1.⁵ The ΔG determined from an average of three separate experiments was $+0.041(1)\ \text{eV}$. The high precision in these measurements is typical of what can be routinely obtained with the redox equilibrium method. Using the well-established oxidation potential of hexamethylbenzene in acetonitrile (1.580 V vs SCE)⁶ gives an oxidation potential for 1,3,5-trimethoxybenzene of 1.539(1) V vs SCE. This latter potential and others similarly obtained were used to generate a redox ladder to measure oxidation potentials for the other substrates described here (see the Supporting Information).

Table 1 lists the oxidation potentials of 11 benzene derivatives with alkoxy substituents determined by the redox equilibrium method described above. The oxidation potentials of 12 aromatic amines determined in an analogous manner are listed in Table 2. The oxidation potentials of 9 acetanilide and oxindole derivatives are listed in Table 3.

Because the cation radicals of benzene derivatives often have similar absorption spectra, which can make applying the redox equilibrium method more challenging, biphenyl derivatives, whose cation radicals typically absorb in different regions, can serve as useful “bridges” in generating a redox ladder. The oxidation potentials of 8 biphenyl derivatives that were used in this capacity are listed in Table 4 (see Redox Ladder in the Supporting Information).

Several experiments were performed to test the reliability, internal consistency, and accuracy of the oxidation potentials reported here. As described above, toluene at 0.5 M in acetonitrile was used as a codonor for cation radical generation. We tested whether the concentration of toluene had any measurable effect on the experimental ΔE_{ox} values. The redox

Table 1. Oxidation Potentials (V vs SCE) for Alkoxybenzenes at 20 °C in Acetonitrile Determined from Redox Equilibrium Experiments ($E_{\text{ox}}^{\text{eq}}$) and the Range of Literature Oxidation Potentials Determined Electrochemically in Acetonitrile ($E_{\text{ox}}^{\text{el}}$)

	compound	($E_{\text{ox}}^{\text{eq}}$) ^{a,b}	($E_{\text{ox}}^{\text{el}}$) ^c
1	diphenyl ether	1.906(6)	1.76–1.97
2	anisole	1.773(6)	1.60–1.81
3	1,3-dimethoxybenzene	1.549(1)	1.30–1.49
4	1,3,5-trimethoxybenzene	1.539(1)	1.35–1.49
5	1,3-benzodioxole	1.458(2)	1.42–1.45
6	1,2-dimethoxybenzene	1.415(3)	1.24–1.46
7	1,2,3-trimethoxybenzene	1.390(3)	1.42
8	1,2-dimethoxy-4-methylbenzene	1.286(4)	1.19–1.30
9	1,4-dimethoxybenzene	1.278(4)	1.06–1.59
10	1,2,3,5-tetramethoxybenzene	1.087(4)	1.03–1.09
11	1,2,4-trimethoxybenzene	1.080(4)	0.98–1.12

^aThe standard deviation in the last significant digit is given in parentheses. ^bThe oxidation potential of 1,2,4,5-tetramethoxybenzene was determined electrochemically to be 0.794(1) V vs SCE in acetonitrile. ^cFrom refs 7–18.

Table 2. Oxidation Potentials (V vs SCE) for Aromatic Amines at 20 °C in Acetonitrile Determined from Redox Equilibrium Experiments ($E_{\text{ox}}^{\text{eq}}$) and the Range of Literature Oxidation Potentials Determined Electrochemically in Acetonitrile ($E_{\text{ox}}^{\text{el}}$)

	compound	($E_{\text{ox}}^{\text{eq}}$) ^a	($E_{\text{ox}}^{\text{el}}$) ^b
12	indole	1.254(4)	1.12–1.61
13	<i>N</i> -methylindole	1.184(5)	1.1–1.58
14	4-cyano- <i>N,N</i> -dimethylaniline	1.146(5)	1.05–1.18
15	4-trifluoromethyl- <i>N,N</i> -dimethylaniline	1.108(4)	1.11
16	2-methylindole	1.106(6)	0.90–1.25
17	3-methylindole	1.085(4)	0.95–1.26
18	4-methylcarboxy- <i>N,N</i> -dimethylaniline	1.058(4)	0.98
19	aniline	1.038(5)	0.8–1.28
20	diphenylmethanamine	0.954(4)	0.8–1.05
21	<i>N</i> -methylaniline	0.928(4)	0.59–1.03
22	4-bromo- <i>N,N</i> -dimethylaniline	0.916(4)	0.86–0.96
23	<i>N,N</i> -dimethylaniline	0.851(2)	0.64–1.01

^aThe standard deviation in the last significant digit is given in parentheses. ^bFrom refs 7 and 19–30

Table 3. Oxidation Potentials (V vs SCE) for Substituted Acetanilides and Oxindoles at 20 °C in Acetonitrile Determined from Redox Equilibrium Experiments ($E_{\text{ox}}^{\text{eq}}$) and the Range of Literature Oxidation Potentials Determined Electrochemically in Acetonitrile ($E_{\text{ox}}^{\text{el}}$)

	compound	($E_{\text{ox}}^{\text{eq}}$) ^a	($E_{\text{ox}}^{\text{el}}$) ^b
24a	4-cyano- <i>N</i> -methylacetanilide	1.944(6)	
25a	4-cyanoacetanilide	1.930(6)	
24b	<i>N</i> -methylacetanilide	1.753(6)	
25b	acetanilide	1.680(4)	1.6–1.90
24c	4-methoxy- <i>N</i> -methylacetanilide	1.402(6)	
25c	4-methoxyacetanilide	1.275(6)	
26	2-oxindole	1.535(3)	
27	<i>N</i> -methyl-2-oxindole	1.495(2)	
28	<i>N</i> ,3,3-trimethyl-2-oxindole	1.516(4)	

^aThe standard deviation in the last significant digit is given in parentheses. ^bFrom refs 7 and 31.

Table 4. Oxidation Potentials (V vs SCE) for Biphenyl Derivatives at 20 °C in Acetonitrile Determined from Redox Equilibrium Experiments ($E_{\text{ox}}^{\text{eq}}$) and the Range of Literature Oxidation Potentials Determined Electrochemically in Acetonitrile ($E_{\text{ox}}^{\text{el}}$)

compound	$(E_{\text{ox}}^{\text{eq}})^a$	$(E_{\text{ox}}^{\text{el}})^b$	
29	2,2'-dimethoxybiphenyl	1.601(3)	1.45–1.51
30	4-methoxybiphenyl	1.503(1)	1.39–1.53
31	4-methoxy-4'-methylbiphenyl	1.425(3)	
32	3,4-dimethoxybiphenyl	1.303(4)	
33	4,4'-dimethoxybiphenyl	1.266(4)	1.26–1.30
34	3,4-dimethoxy-4'-methylbiphenyl	1.252(5)	
35	3,4,4'-trimethoxybiphenyl	1.161(4)	
36	3,3',4,4'-tetramethoxybiphenyl	1.107(4)	1.09

^aThe standard deviation in the last significant digit is given in parentheses. ^bFrom refs 7 and 32–35.

equilibrium measured for the pair 1,4-dimethoxybenzene/4,4'-dimethoxybiphenyl gave $\Delta E_{\text{ox}} = 0.012(1)$ eV with 0.5 M toluene and 0.011(1) eV with 0.1 M toluene, showing that the concentration of toluene had no measurable effect on the measured value of ΔE_{ox} .

The internal consistency of the E_{ox} values was tested by determining the oxidation of 1,3-benzodioxole (**5**) using three different paths along the redox ladder starting from 1,3,5-trimethoxybenzene (**4**). The direct redox equilibration of **4** and **5** gave $E_{\text{ox}}(\mathbf{5}) = 1.458(1)$ V vs SCE. A path starting with **4** that involved two redox equilibrations gave $E_{\text{ox}}(\mathbf{5}) = 1.458(2)$ V vs SCE, and a path involving four redox equilibrations gave 1.459(3) V vs SCE. The excellent agreement among these data illustrates the internal consistency of the ΔE_{ox} values obtained by redox equilibration.

Lastly, the accuracy of the oxidation potentials determined by redox equilibration was tested by comparing the E_{ox} value for 1,4-dimethoxybenzene (**9**), which was obtained from five equilibration “steps” along the redox ladder starting from hexamethylbenzene, to the reversible oxidation potential determined by cyclic voltammetry. The two potentials for **9** were 1.278(4) and 1.282(5) V vs SCE, respectively. The excellent agreement between the oxidation potentials demonstrates the accuracy (and precision) of the redox equilibrium method.

As can be seen from the data in Tables 1–4, in general the redox equilibrium method provides much more accurate oxidation potentials than those previously available from electrochemical measurements. The new oxidation potentials provide reliable data that can be used to test a variety of thermodynamic and kinetic relationships. As mentioned above, some of these data have already been used for a critical reexamination of the Rehm–Weller data set.¹

The vast majority of the oxidation potentials follow well-established chemical trends. For example, for the methoxy-substituted aromatics (Tables 1 and 4), the oxidation potential generally decreases as the number of electron-donating methoxy groups increases, although the position of the substituents obviously matters. For example, 1,4-dimethoxybenzene has a lower oxidation potential than 1,2-dimethoxybenzene, which in turn is lower than that of 1,3-dimethoxybenzene. A similar trend is found for 1,2,4-trimethoxybenzene versus 1,2,3-trimethoxybenzene versus 1,3,5-trimethoxybenzene. These trends are consistent with the relative abilities of the substitution patterns to reinforce conjugative stabilization of the cation radicals. Not

surprisingly, the oxidation potential data also show that compounds containing substituents that are more electron-donating in general have lower oxidation potentials. For example, the oxidation potential of acetanilide (1.680 V vs SCE) is significantly higher than that of aniline (1.038 V vs SCE). Similarly, aniline has a higher oxidation potential than *N*-methylaniline (0.928 V vs SCE), which in turn has a higher oxidation potential than *N,N*-dimethylaniline (0.851 V vs SCE).

Oxidation Potentials of Acetanilides. Interestingly, the trend of *N*-methyl substitution that results in a lowering of the aniline oxidation potentials is *not* followed for the corresponding acetanilides (Table 3). For example, *N*-methylacetanilides **24a–c** all have oxidation potentials that are greater than those of the corresponding acetanilides **25a–c**. We hypothesized that the differences in the oxidation potentials of the acetanilides and the *N*-methylacetanilides might be related to conformational factors, as it is well-known that acetanilides lacking ortho substituents are generally planar whereas *N*-methylacetanilides have large twist angles about the N–Ar bond.³⁶ This hypothesis was tested experimentally by measuring the oxidation potentials of 2-oxindole (**26**) and *N*-methyl-2-oxindole (**27**), which are constrained to have planar structures. The cation radicals of **26** and **27** were first generated and compared to that of *N*,3,3-trimethyl-2-oxindole (**28**) in order to test whether either **26**^{•+} or **27**^{•+} underwent rapid enolization upon oxidation.³⁷ The close similarity of the spectra for **26**^{•+}–**28**^{•+} (Figure 2) shows that neither **26**^{•+} nor **27**^{•+} underwent rearrangement upon oxidation, at least within the time scale of the measurements.

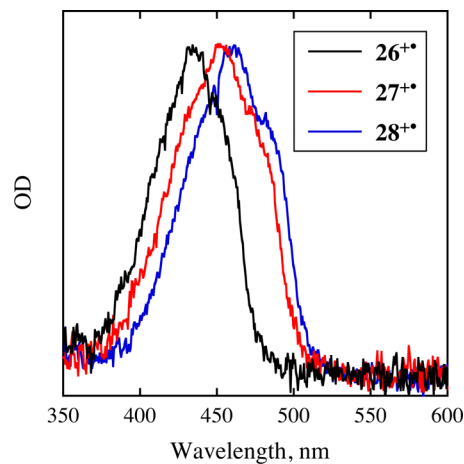
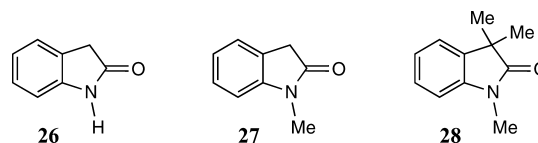


Figure 2. Transient spectra in acetonitrile for the cation radicals of 2-oxindole (**26**^{•+}) (black), *N*-methyl-2-oxindole (**27**^{•+}) (red), and *N*,3,3-trimethyl-2-oxindole (**28**^{•+}) (blue).



Redox equilibrium experiments showed that **26** has a higher oxidation potential than **27** [1.535(3) vs 1.495(2) V vs SCE]. The oxidation potential of **28** [1.516(3) V vs SCE] was found to be slightly higher than that of **27**, which can be reasonably attributed to decreased solvation of **28**^{•+} due to a steric effect. The higher oxidation potential of **26** versus **27** is opposite to the results with the acetanilides. These results are consistent with

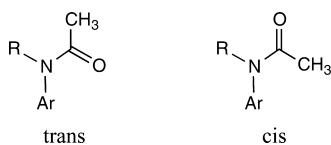
Table 5. Calculated Energy Differences (in kcal/mol) between the Cis and Trans Conformers of Acetanilides (25a–c), *N*-Methylacetanilides (24a–c), and Their Cation Radicals in Vacuo, (ΔE_{c-t})_v, and in Acetonitrile, (ΔE_{c-t})_{ACN}

amide	substituent	(ΔE_{c-t}) _v	(ΔE_{c-t}) _{ACN}	amide ⁺	(ΔE_{c-t}) _v	(ΔE_{c-t}) _{ACN}
25a	<i>p</i> -CN	3.7	5.4	25a ⁺	5.2	4.6
25b	H	2.7	4.7	25b ⁺	4.8	4.4
25c	<i>p</i> -OMe	2.4	4.2	25c ⁺	5.9	5.0
24a	<i>p</i> -CN	−0.83	0.30	24a ⁺	– ^a	– ^a
24b	H	−2.6	−1.6	24b ⁺	1.6	0.92
24c	<i>p</i> -OMe	−3.0	−2.2	24c ⁺	2.6	0.94

^aThe cis conformer is not an energy minimum.

the hypothesis that conformational effects play a role in the higher oxidation potentials of *N*-methylacetanilides 24a–c versus acetanilides 25a–c. We resorted to molecular orbital calculations to further test this hypothesis.

We begin by discussing our computational results for acetanilides 25a–c. Density functional theory calculations (B3LYP/6-31+G**) using the SM8 solvation model³⁸ to simulate acetonitrile showed that 25a–c all prefer a trans conformation (see Table 5 and below), consistent with both experimental evidence and other MO calculations.³⁶ As also shown in Table 5, our calculations revealed a strong energetic preference for the trans conformer for the acetanilide cation radicals 25a–c⁺. On the basis of these results, 25a–c are not predicted to undergo conformational changes upon one-electron oxidation. Before the *N*-methylacetanilides are discussed, it is first instructive to analyze the structural predictions for the cis conformers of the acetanilides and their cation radicals.



In contrast to the trans conformers of 25a–c, which have twist angles (ϕ) around the N–Ar bond of $\sim 0^\circ$, the cis conformers are predicted to have twist angles of 70.0° , 40.0° , and 29.3° , respectively. For the cis conformers of 25a–c⁺, however, the calculated twist angles are near zero (0.2° , 0.3° , and 0.2° , respectively). These results show that acetanilide cation radicals prefer a conformation where the unpaired spin density on the amide nitrogen is conjugated with the aromatic ring, even when it is electron-deficient, as in 25c⁺. As described below, this insight helps in understanding the conformational preferences of the *N*-methylacetanilides.

Density functional theory calculations showed that the neutral *N*-methylacetanilides 24a–c all prefer a cis conformation with a nearly planar amide geometry, as measured by the Winkler–Dunitz³⁹ torsion angle τ (0.3° , 1.7° , and 3.5° , respectively), and large N–Ar twist angles (87.1° , 81.0° , and 74.2° , respectively). These results are consistent with both experiments and other MO calculations on *N*-methylacetanilide conformations.³⁶ As shown in Table 5, the computed energy differences between the cis and trans conformers in vacuo for 24b and 24c are comparable (-2.6 and -3.0 kcal/mol, respectively) and considerably smaller for 24a (-0.83 kcal/mol). These differences are computed to be smaller in acetonitrile by ~ 1 kcal/mol, such that the cis conformers of 24b and 24c are predicted to be lower by 1.6 and 2.2 kcal/mol, respectively. In the case of 24a, the trans conformer is predicted to be lower than the cis conformer by 0.3 kcal/mol in acetonitrile.

Interestingly, calculations for the *N*-methylacetanilide cation radicals 24a–c⁺ show that the trans conformations are preferred in both vacuum and acetonitrile (see Table 5). A notable structural feature of the trans conformations of 24a–c⁺ is that the N–Ar twist angles are much smaller than those for the cis conformers of the neutral amides (19.6° vs 87.1° , 14.0° vs 81.0° , and 11.6° vs 74.2° for 24a–c⁺ vs 24a–c, respectively). The smaller twist angle for the cation radicals is consistent with the preference cited above for the cis conformers of 25a–c⁺ versus 25a–c. As should be clear, enforcing a small N–Ar twist angle for the cis conformation of the *N*-methylacetanilide cation radicals 24a–c⁺ would lead to a destabilizing interaction between the acyl methyl group and one of the ortho hydrogens in the aromatic ring. Thus, 24a–c⁺ presumably adopt a trans conformation to simultaneously avoid this steric interaction and minimize the N–Ar twist angle in the cation radicals. The preferred conformations for 24a–c⁺ come with other structural effects, most notably that the amide functionality is predicted to be twisted about the N–C(O) bond. The degrees of twisting, as measured by the τ angles, are calculated to be 18.7° , 33.3° , and 35.4° for 24a–c⁺, respectively. The twisting in the cation radicals is presumably to avoid steric interactions between the acyl methyl group and the *N*-methyl group in the trans conformers. Thus, the computations show that whereas conformations of 24a–c⁺ maximize orbital overlap with relatively small twist angles in the trans conformations, they also pay a “price” in terms of their twisted amide conformations. Clearly, a balance of factors is important in determining the energies of the cation radical conformations.

To test whether the predicted change in conformational preference for 24a–c versus 24a–c⁺ is relevant for understanding the relative oxidation potentials of 24a–c versus 25a–c, it was important to determine whether the energy barriers separating the cis and trans conformers of 24a–c⁺ were sufficiently low to allow rapid conformational interconversion on the time scale of the nanosecond redox equilibrium experiments ($\sim 1 \mu\text{s}$). Energy profiles for rotation around the N–Ar bond of 24a–c⁺ computed in vacuo and in acetonitrile were found to be low in all cases (see the Supporting Information). The computed barriers for cis \rightarrow trans conformational interconversion for 24b⁺ and 24c⁺ in acetonitrile were ~ 2.1 and ~ 0.4 kcal/mol, respectively. For 24a⁺, the cis conformer is not predicted to have an energy minimum in acetonitrile. On the basis of these results, one can confidently conclude that one-electron oxidation of 24a–c will lead to extremely rapid conversion of 24a–c⁺ to their trans conformers in acetonitrile.

The computational results discussed above can be used to qualitatively understand why *N*-methylacetanilides 24a–c have higher oxidation potentials than acetanilides 25a–c. For the acetanilides, the trans conformers are more stable for both the

neutral molecules and their corresponding cation radicals. In these conformations both **25a–c** and **25a–c⁺** are relatively unstrained, with amide functionalities that are nearly planar and N–Ar twist angles that are close to zero. In contrast, for the *N*-methylacetanilides, one-electron oxidation of the more stable *cis* conformers leads to cation radicals that cannot achieve small twist angles without severe steric interactions. Conformational interconversion to the *trans* conformers permits smaller but still significant twist angles to be achieved ($\tau \approx 19\text{--}36^\circ$), but at the cost of twisted amide groups, which destabilize the cation radicals. Thus, the *trans* conformers of **24a–c⁺** are more strained than the neutral *cis* conformers of **24a–c**. To summarize, the one-electron oxidations of **25a–c** involve relatively strain-free transformations, whereas the oxidations of **24a–c** produce cation radicals that are more strained. The consequence is that *N*-methylacetanilides **24a–c** have higher oxidation potentials than the correspondingly substituted acetanilides **25a–c**.⁴⁰

The accurate oxidation potentials experimentally determined for both **24a–c** and **25a–c** provided an opportunity to critically test the ability of the computational model to quantitatively predict their relative oxidation potentials. We initially tested the model for predicting the relative oxidation potentials for oxindoles **26–28**, which are devoid of complications due to conformational effects. Table 6 shows a comparison of the

Table 6. Oxidation Potentials (V vs SCE) for Oxindoles 26–28 in Acetonitrile Determined from Redox Equilibrium Experiments ($E_{\text{ox}}^{\text{eq}}$), Differences in Experimental Oxidation Potentials ($\Delta E_{\text{ox}}^{\text{eq}}$), and Differences in Calculated Oxidation Potentials ($\Delta E_{\text{ox}}^{\text{calc}}$) in Acetonitrile

Oxindole	$(E_{\text{ox}}^{\text{eq}})^a$	$(\Delta E_{\text{ox}}^{\text{eq}})^a$	$\Delta E_{\text{ox}}^{\text{calc}}$
26	1.535(3)	} –0.040(4)	–0.066
27	1.495(2)		
28	1.516(4)	} +0.021(4)	+0.021

^aThe standard deviation in the last significant digit is given in parentheses.

experimental differences in the oxidation potentials of **26–28** in acetonitrile to those predicted computationally. Gratifyingly, the computational model correctly predicts the relative signs of the ΔE_{ox} values. The predicted ΔE_{ox} difference between **27** and **28** is in excellent agreement with experiment, whereas that between **26** and **27** differs from the experimental value by 0.026 eV. These results were sufficiently encouraging to extend the study to the prediction of ΔE_{ox} values for the *N*-methylacetanilides **24a–c** and acetanilides **25a–c**.

The relative oxidation potentials of acetanilides **25a–c** were computed by taking the energy differences between the most stable conformations of the cation radicals and those of the neutral molecules after applying the computed SM8 solvation free energies in acetonitrile. As described above, for secondary amides **25a–c**, the *trans* conformers are the most stable for both the neutral amides and the corresponding cation radicals. For the tertiary amides **24b** and **24c**, the *cis* conformers are most stable for the neutral amides and the *trans* conformer for their cation radicals. For **24a**, the *trans* conformer is predicted to be

more stable for both the neutral molecule and the cation radical in acetonitrile. Table 7 shows the comparison of the

Table 7. Oxidation Potentials (V vs SCE) for Amides 24 and 25 in Acetonitrile Determined from Redox Equilibrium Experiments ($E_{\text{ox}}^{\text{eq}}$), Differences in Experimental Oxidation Potentials ($\Delta E_{\text{ox}}^{\text{eq}}$), and Differences in Calculated Oxidation Potentials ($\Delta E_{\text{ox}}^{\text{calc}}$) in Acetonitrile

Amide	Substituent	$(E_{\text{ox}}^{\text{eq}})^a$	$(\Delta E_{\text{ox}}^{\text{eq}})^a$	$\Delta E_{\text{ox}}^{\text{calc}}$
24a	} <i>p</i> -CN	1.944(6)	} 0.014(8)	–0.098
25a		1.930(6)		
24b	} H	1.735(6)	} 0.055(7)	0.038
25b		1.680(4)		
24c	} <i>p</i> -OMe	1.402(6)	} 0.127(8)	0.129
25c		1.275(6)		

^aThe standard deviation in the last significant digit is given in parentheses.

experimental and computed ΔE_{ox} values for the secondary versus tertiary amides. The agreement between experiment and theory is good for the **24b/25b** and **24c/25c** pairs, with discrepancies of only 0.017 and 0.002 eV, respectively. The result for the **24a/25a** pair is clearly worse; the predicted ΔE_{ox} has the wrong sign and is off by 0.112 eV. At present, the reason for the uniquely poor agreement of the **24a/25a** pair is unclear. One possibility is that the training set of solvation free energies used to parametrize the SM8 solvation model contains too few molecules with a nitrile functionality.⁴¹ Further work will be needed to test this hypothesis. The poor prediction for the **24a/25a** pair aside, the SM8 model combined with DFT nonetheless appears to be a promising method for predicting relative oxidation potentials in acetonitrile.⁴² Importantly, accurate oxidation potentials like those provided here will allow this and other solvation models to be critically tested and refined, which is especially important because of the limited availability of accurate thermodynamic data for organic ion radicals to date.

Oxidation Potentials of Benzenes versus Biphenyls.

With a number of accurate oxidation potentials for biphenyl and benzene derivatives in hand, it was possible to determine whether there is a correlation between compounds with analogous substitution patterns. Biphenyls with one substituent at C4 or two substituents at C3 and C4 are structurally similar to the corresponding mono- and 1,2-disubstituted benzenes. Analogously, 4,4'- and 3,4,4'-substituted biphenyls share a structural similarity to 1,4- and 1,2,4-substituted benzenes, respectively. Including the parent compounds, data for eight such analogous pairs with methyl or methoxy substituents are available from this and prior work.³ A plot of the oxidation potentials of these biphenyl derivatives versus those of the analogous benzenes is shown in Figure 3 (circles). As is clear, the oxidation potentials show a remarkably linear correlation. The slope of the plot (0.56) shows that the oxidation potentials of the biphenyls are less sensitive to substitution than those of the benzenes. This is consistent with the biphenyl cation radicals being more delocalized than the benzene cation radicals. The

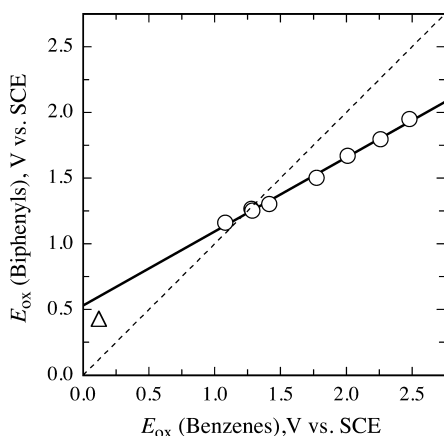


Figure 3. Oxidation potentials of methyl- and methoxy-substituted biphenyl and benzene derivatives in acetonitrile (see the Supporting Information for the data table).

correlation predicts that for substituted benzenes with E_{ox} less than ~ 1.25 V vs SCE in acetonitrile, the relative magnitude of the oxidation potentials of the benzenes and the analogous biphenyls should be reversed. That this is indeed the case is demonstrated by the relative oxidation potentials of 4,4'-bis(dimethylamino)biphenyl ($E_{\text{ox}} = 0.43$ V vs SCE)^{30e} and N,N,N',N' -tetramethyl-*p*-phenylenediamine ($E_{\text{ox}} = 0.12$ V vs SCE).^{30e} Although this data point (triangle) does not fit as well on the correlation of the methoxy- and methyl-substituted benzene/biphenyl derivatives, the trend is clear: whereas the oxidation potential of unsubstituted biphenyl is 0.53 V lower than that of benzene, that of the electron-rich bis(diamino)-substituted derivative is 0.31 V higher than that of the corresponding benzene.

CONCLUSIONS

The accurate oxidation potentials for the 40 substrates established here combined with those previously determined^{3,43} by redox equilibrium methods provide a large, thermodynamically meaningful set of benchmark data that can be confidently used to test a variety of thermodynamic and kinetic relationships as well as reanalyze prior experiments. The utility of such accurate oxidation potentials has been demonstrated here and elsewhere.¹ Further applications will undoubtedly be forthcoming.

EXPERIMENTAL SECTION

Materials. Acetonitrile (99.93+%, Baker, HPLC grade, <10 ppm H₂O) was purified by passing it over a bed of activated alumina.⁴⁴ *N*-Methylquinolinium hexafluorophosphate (NMQ⁺) was prepared as previously described.⁴⁵ Most compounds were obtained from commercial sources and were purified by either fractional distillation (liquids) or recrystallization (solids). Biphenyls **31**,⁴⁶ **32**,⁴⁷ **34**,⁴⁷ **35**,⁴⁸ and **36**⁴⁹ were prepared by literature methods, as were amides **24a**,⁵⁰ **24c**,^{36h} and **25a**.⁵¹

Redox Equilibrium Measurements. The transient absorption apparatus and the methodology have been described previously.³ All of the measurements were carried out at ambient temperature (293 ± 1 K). Dioxygen-saturated acetonitrile solutions containing ~ 1 mM NMQ⁺ and 0.5 M toluene were excited at 343 nm (~ 1 mJ/pulse; 7 ns pulses). Donor concentrations ranged from ~ 1 to ~ 20 mM. Transient spectra were typically recorded ~ 1 – 2 μ s after the laser pulse. The oxidation potential differences are averages of 2–3 independent determinations, each of which involved 2–3 equilibrium measurements at 3–4 different concentrations of substrates.

Cyclic Voltammetry. Cyclic voltammetry experiments were performed at scan rates ranging from 0.1 to 1 V/s in argon-purged acetonitrile containing 0.1 M tetra-*n*-butylammonium tetrafluoroborate and ~ 5 mM substrate (see the Supporting Information for voltammograms). The derived standard potentials were electronically corrected (positive feedback) for Ohmic drop. All of the experiments were conducted with a standard three-electrode setup in a conical electrochemical cell encased in a jacket that allowed the temperature to be controlled at 20 °C by means of a thermostated circulating bath. The working electrode was a glassy carbon disk (0.5 mm dia.) that was polished using a 1 μ m diamond paste. The counter electrode was a glassy carbon disk (0.3 cm dia.). All of the potentials were recorded versus an SCE electrode that was isolated from the working electrode compartment by a salt bridge with a ceramic frit that allowed ionic conduction between the two solutions while avoiding appreciable contamination. The average E° values determined for 1,4-dimethoxybenzene, 4,4'-dimethoxybiphenyl, and 1,2,4,5-tetramethoxybenzene were 1.282(4), 1.272(1), and 0.794(1) V vs SCE.⁵

Computations. All of the calculations were carried out with Spartan'14⁵² using the B3LYP hybrid density functional method.⁵³ Open-shell calculations were performed with the unrestricted UB3LYP method. Geometry optimizations and vibrational analyses were performed with a 6-31+G** basis set. The SM8 solvent model³⁸ was used to model the reaction solvent (acetonitrile). The calculated solvation free energies were determined from single-point calculations on the optimized gas-phase geometries. Vibrational frequencies were determined by using the analytic Hessian calculated for each local minimum. In all cases, local minima had positive vibrational frequencies. The N–Ar twist angle was defined as the angle between the plane defined by the phenyl-group carbon bonded to the amide nitrogen and the adjacent carbons in the phenyl ring and the plane defined by the amide nitrogen atom, the carbonyl carbon, and the other substituent attached to the nitrogen atom (H or CH₃).

ASSOCIATED CONTENT

Supporting Information

Redox ladder; redox equilibrium spectra; cyclic voltammograms; energy as a function of amide cation radical torsion angle; calculated energies in vacuo, SM8 solvation free energies in acetonitrile, expectation values of S^2 ($\langle S^2 \rangle$), and geometries; and oxidation potentials of substituted benzene and biphenyl derivatives for Figure 3. This material is available free of charge via the Internet at <http://pubs.acs.org>.

AUTHOR INFORMATION

Corresponding Authors

*E-mail: gonzalo.guirado@uab.cat.
*E-mail: farid@chem.rochester.edu.
*E-mail: jpd@chem.rochester.edu.

Notes

The authors declare no competing financial interest.

ACKNOWLEDGMENTS

Research at the University of Rochester was supported by a grant from the National Science Foundation (CHE-1057615). Financial support by the Universitat Autònoma de Barcelona (APOSTA Research Program) and the Spanish Ministry of Economy and Competitiveness (MINECO) (Project CTQ2012-30853) is gratefully acknowledged.

REFERENCES

- (1) Farid, S.; Dinnocenzo, J. P.; Merkel, P. B.; Young, R. H.; Shukla, D.; Guirado, G. *J. Am. Chem. Soc.* **2011**, *133*, 11580.
- (2) (a) Rehm, D.; Weller, A. *Isr. J. Chem.* **1970**, *8*, 259. (b) Rehm, D.; Weller, A. *Ber. Bunsen-Ges. Phys. Chem.* **1969**, *73*, 834.

(3) (a) Guirado, G.; Fleming, C. N.; Lingenfelter, T. G.; Williams, M. L.; Zuillhof, H.; Dinnocenzo, J. P. *J. Am. Chem. Soc.* **2004**, *126*, 14086. (b) Merkel, P. B.; Luo, P.; Dinnocenzo, J. P.; Farid, S. *J. Org. Chem.* **2009**, *74*, S163. (c) Luo, P.; Dinnocenzo, J. P.; Merkel, P. B.; Young, R. H.; Farid, S. *J. Org. Chem.* **2012**, *77*, 1632.

(4) For reviews of the redox equilibrium method applied in water and alcoholic solvents, see: (a) Steenzen, S. *Landolt-Börnstein* **1985**, *13e*, 147. (b) Wardman, P. J. *Phys. Chem. Ref. Data* **1989**, *18*, 1637. (c) Stanbury, D. M. In *General Aspects of the Chemistry of Radicals*; Alfassi, Z. B., Ed.; Wiley: New York, 1999; Chapter 11.

(5) The standard deviation in the last significant digit is given in parentheses.

(6) Amatore, C.; Lefrou, C. *J. Electroanal. Chem.* **1992**, *325*, 239.

(7) Literature oxidation potentials in acetonitrile not referenced to SCE were corrected according to ref 7a: (a) Mann, C. K.; Barnes, K. K. *Electrochemical Reactions in Nonaqueous Systems*; Marcel Dekker: New York, 1970; p 26. For the Ag/AgI reference electrode, the correction to SCE was applied according to ref 7b: (b) Rondinini, S.; Longhi, P.; Mussini, T. *Ann. Chim. (Rome, Italy)* **1977**, *67*, 48.

(8) Literature references for the oxidation potential of diphenyl ether: (a) Janissek, P. R.; Pardini, V. L.; Viertler, H. *J. Chem. Soc., Chem. Commun.* **1987**, 576. (b) Yamada, F.; Nishiyama, T.; Nakai, Y.; Nishii, S. *Technol. Rep. Kansai Univ.* **1988**, *30*, 91.

(9) Literature references for the oxidation potential of anisole: (a) Lund, H. *Acta Chem. Scand.* **1957**, *11*, 1323. (b) Zweig, A.; Hodgson, W. G.; Jura, W. H. *J. Am. Chem. Soc.* **1964**, *86*, 4124. (c) Miller, L. L.; Nordblom, G. D.; Mayeda, E. A. *J. Org. Chem.* **1972**, *37*, 916. (d) Perrin, C. L. *J. Am. Chem. Soc.* **1977**, *99*, 5516. (e) Birch, A. J.; Slobbe, J. *Aust. J. Chem.* **1978**, *31*, 2555. (f) Majima, T.; Pac, C.; Nakasone, A.; Sakurai, H. *J. Am. Chem. Soc.* **1981**, *103*, 4499. (g) Kawenoki, I.; Keita, B.; Kossanyi, J.; Nadjo, L. *Bull. Soc. Chim. Fr.* **1982**, *104*, (h) Burget, D.; Jacques, P.; Vauthey, E.; Suppan, P.; Haselbach, E. *J. Chem. Soc., Faraday Trans.* **1994**, *90*, 2481. (i) van Walree, C. A.; Roest, M. R.; Schuddeboom, W.; Jenneskens, L. W.; Verhoeven, J. W.; Warman, J. M.; Kooijman, H.; Spek, A. L. *J. Am. Chem. Soc.* **1996**, *118*, 8395. (j) Branchi, B.; Galli, C.; Gentili, P. *Org. Biomol. Chem.* **2005**, *3*, 2604. (k) Tajima, T.; Nakajima, A. *J. Am. Chem. Soc.* **2008**, *130*, 10496. (l) Ohkubo, K.; Mizushima, K.; Iwata, R.; Fukuzumi, S. *Chem. Sci.* **2011**, *2*, 715.

(10) Literature references for the oxidation potential of 1,3-dimethoxybenzene: (a) Reference 9e. (b) Suzuki, T.; Fujii, H.; Yamashita, Y.; Kabuto, C.; Tanaka, S.; Harasawa, M.; Mukai, T.; Miyashi, T. *J. Am. Chem. Soc.* **1992**, *114*, 3034. (c) Patz, M.; Mayr, H.; Maruta, J.; Fukuzumi, S. *Angew. Chem.* **1995**, *107*, 1351. (d) Tommasino, J.-B.; Bronde, A.; Médebille, M.; Thomalla, M.; Langlois, B. R.; Billard, T. *Synlett* **2002**, 1697. (e) Fukuzumi, S.; Yuasa, J.; Satoh, N.; Suenobu, T. *J. Am. Chem. Soc.* **2004**, *126*, 7585. (f) Reference 9l. (g) Breton, G. W.; Hoke, K. R. *J. Org. Chem.* **2013**, *78*, 4697.

(11) Literature references for the oxidation potential of 1,3,5-trimethoxybenzene: (a) Reference 9b. (b) Reference 9g. (c) Mizuno, K.; Yoshioka, K.; Otsuji, Y. *Chem. Lett.* **1983**, 941. (d) Reference 10c. (e) Reference 9f. (f) Pouliquen, J.; Wintgens, V.; Toscano, V.; Jaafar, B. B.; Tripathi, S.; Kossanyi, J.; Valat, P. *Can. J. Chem.* **1984**, *62*, 2478. (g) Wolffe, I.; Lodaya, J.; Sauerwein, B.; Schuster, G. B. *J. Am. Chem. Soc.* **1992**, *114*, 9304. (h) Dileesh, S.; Gopidas, K. R. *J. Photochem. Photobiol., A* **2004**, *162*, 115. (i) Reference 9l. (j) Reference 10g.

(12) Literature references for the oxidation potential of 1,3-benzodioxole: (a) Yan, B.-Z.; Zhang, Z.-G.; Yuan, H.-C.; Wang, L.-C.; Xu, J.-H. *J. Chem. Soc., Perkin Trans. 2* **1994**, 2545. (b) Rudenko, A. P.; Pragst, F. *Russ. J. Org. Chem.* **1998**, *34*, 1589.

(13) Literature references for the oxidation potential of 1,2-dimethoxybenzene: (a) Reference 9b. (b) Reference 9f. (c) Reference 11f. (d) Reference 10b. (e) Deffieux, D.; Fabre, I.; Courseille, C.; Quideau, S. *J. Org. Chem.* **2002**, *67*, 4458. (f) Reference 10e. (g) Reference 9j. (h) Reference 9k. (i) Reference 9l.

(14) Literature references for the oxidation potential of 1,2,3-trimethoxybenzene: (a) Reference 9b. (b) Reference 9l.

(15) Literature references for the oxidation potential of 1,2-dimethoxy-4-methylbenzene: (a) Palmquist, U.; Nilsson, A.; Parker,

V. D.; Ronlan, A. *J. Am. Chem. Soc.* **1976**, *98*, 2571. (b) Reference 9j. (c) Reference 9l.

(16) Literature references for the oxidation potential of 1,4-dimethoxybenzene: (a) Reference 9b. (b) Reference 9e. (c) Reference 9f. (d) Reference 9g. (e) Reference 11f. (f) Onodera, K.; Furusawa, G.-I.; Kojima, M.; Tsuchiya, M.; Aihara, S.; Akaba, R.; Sakuragi, H.; Tokumaru, K. *Tetrahedron* **1985**, *41*, 2215. (g) Anelli, P. L.; Ashton, P. R.; Ballardini, R.; Balzani, V.; Delgado, M.; Gandolfi, M. T.; Goodnow, T. T.; Kaifer, A. E.; Philp, D. *J. Am. Chem. Soc.* **1992**, *114*, 193. (h) Reference 10b. (i) Reference 9h. (j) Benniston, A. C.; Harriman, A.; Lynch, V. M. *J. Am. Chem. Soc.* **1995**, *117*, 5275. (k) Rehm, J. M.; McLendon, G. L.; Fauchet, P. M. *J. Am. Chem. Soc.* **1996**, *118*, 4490. (l) Ballardini, R.; Balzani, V.; Credi, A.; Brown, C. L.; Gillard, R. E.; Montalti, M.; Philp, D.; Stoddart, J. F.; Venturi, M.; White, A. J. P.; Williams, B. J.; Williams, D. J. *J. Am. Chem. Soc.* **1997**, *119*, 12503. (m) Chauzov, V. A.; Parchinskii, V. Z.; Sinel'shchikova, E. V.; Parfenov, N. N.; Petrosyan, V. A. *Russ. Chem. Bull.* **2002**, *51*, 998. (n) Reference 13e. (o) Reference 10d. (p) Shukla, D.; Liu, G.; Dinnocenzo, J. P.; Farid, S. *Can. J. Chem.* **2003**, *81*, 744. (q) Svith, H.; Jensen, H.; Almstedt, J.; Andersson, P.; Lundback, T.; Daasbjerg, K.; Jonsson, M. *J. Phys. Chem. A* **2004**, *108*, 4805. (r) Zeng, C.-C.; Becker, J. Y. *J. Org. Chem.* **2004**, *69*, 1053. (s) Reference 10e. (t) Reference 9j. (u) Yuasa, J.; Fukuzumi, S. *Chem. Commun.* **2006**, 561. (v) Sunahara, H.; Urano, Y.; Kojima, H.; Nagano, T. *J. Am. Chem. Soc.* **2007**, *129*, 5597. (w) Reference 10g.

(17) Literature references for the oxidation potential of 1,2,3,5-tetramethoxybenzene: (a) Reference 9b. (b) Reference 11g.

(18) Literature references for the oxidation potential of 1,2,4-trimethoxybenzene: (a) Reference 9b. (b) Reference 16k. (c) Reference 10e. (d) Reference 16u. (e) Reference 9j. (f) Reference 9l.

(19) Literature references for the oxidation potential of indole: (a) Waltman, R. J.; Diaz, A. F.; Bargon, J. *J. Phys. Chem.* **1984**, *88*, 4343. (b) Giessler, A.; Steckhan, E.; Wiest, O.; Knoch, F. *J. Org. Chem.* **1991**, *56*, 1405. (c) Newman, J. D. S.; Blanchard, G. J. *Langmuir* **2006**, *22*, 5882. (d) Huvaere, K.; Skibsted, L. H. *J. Am. Chem. Soc.* **2009**, *131*, 8049. (e) Yin, B.; Wang, L.; Inagi, S.; Fuchigami, T. *Tetrahedron* **2010**, *66*, 6820.

(20) Literature references for the oxidation potential of *N*-methylindole: (a) Reference 19a. (b) Pozkarskii, A. F.; Kuz'menko, V. V.; Bumber, A. A.; Petrov, É. S.; Terekhova, M. I.; Chikina, N. L.; Nanavyan, I. M. *Chem. Heterocycl. Compd.* **1989**, *25*, 180. (c) Reference 19b. (d) Berlin, A.; Canavesi, A.; Schiavon, G.; Zecchin, S.; Zotti, G. *Tetrahedron* **1996**, *52*, 7947. (e) Reference 19d.

(21) Literature references for the oxidation potential of 4-cyano-*N,N*-dimethylaniline: (a) Macdonald, T. L.; Gutheim, W. G.; Martin, R. B.; Guengerich, F. P. *Biochemistry* **1989**, *28*, 2071. (b) Fukuzumi, S.; Shimoosako, K.; Suenobu, T.; Watanabe, Y. *J. Am. Chem. Soc.* **2003**, *125*, 9074. (c) Baciocchi, E.; Bietti, M.; Gerini, M. F.; Lanzalunga, O. *J. Org. Chem.* **2005**, *70*, 5144.

(22) Literature reference for the oxidation potential of 4-trifluoromethyl-*N,N*-dimethylaniline: Dombrowski, G. W.; Dinnocenzo, J. P.; Zielinski, P. A.; Farid, S.; Wosinska, Z. M.; Gould, I. R. *J. Org. Chem.* **2005**, *70*, 3791.

(23) Literature references for the oxidation potential of 2-methylindole: (a) Alberti, A.; Carloni, P.; Ebersson, L.; Greci, L.; Stipa, P. *J. Chem. Soc., Perkin Trans. 2* **1997**, 887. (b) Reference 19a. (c) Reference 20d.

(24) Literature references for the oxidation potential of 3-methylindole: (a) Reference 19a. (b) Reference 20d. (c) Reference 19d. (d) Reference 19e.

(25) Literature reference for the oxidation potential of 4-methylcarboxy-*N,N*-dimethylaniline: Renaud, R. N.; Stephens, C. J.; Brochu, G. *Can. J. Chem.* **1984**, *62*, 565.

(26) Literature references for the oxidation potential of aniline: (a) Reference 9a. (b) Párkányi, C.; Zahradník, R. *Collect. Czech. Chem. Commun.* **1965**, *30*, 4287. (c) Lutskii, A. E.; Beilis, Yu. I.; Fedorchenko, V. I. *Zh. Obshch. Khim.* **1972**, *42*, 2535. (d) Jones, P. R.; Drews, M. J.; Johnson, J. K.; Wong, P. S. *J. Am. Chem. Soc.* **1972**, *94*, 4595. (e) Sasaki, K.; Kitani, A.; Tsuboi, M. *Nippon Kagaku Kaishi* **1973**, 2269. (f) Hand,

- R. L.; Nelson, R. F. *J. Am. Chem. Soc.* **1974**, *96*, 850. (g) Reference 9g. (h) Reference 11f. (i) Calderwood, T. S.; Johlman, C. L.; Roberts, J. L.; Wilkins, C. L.; Sawyer, D. T. *J. Am. Chem. Soc.* **1984**, *106*, 4683. (j) Liu, W.-Z.; Bordwell, F. G. *J. Org. Chem.* **1996**, *61*, 4778. (k) Pal, H.; Nagasawa, Y.; Tominaga, K.; Yoshihara, K. *J. Phys. Chem.* **1996**, *100*, 11964. (l) Jonsson, M.; Wayner, D. D. M.; Luszyk, J. *J. Phys. Chem.* **1996**, *100*, 17539. (m) Shirota, H.; Pal, H.; Tominaga, K.; Yoshihara, K. *J. Phys. Chem. A* **1998**, *102*, 3089. (n) Zhuikov, V. V. *Russ. J. Gen. Chem.* **1999**, *69*, 1796. (o) Saito, K.; Kawamura, A.; Kanie, T.; Ueda, Y.; Kondo, S. *Heterocycles* **2001**, *55*, 1071.
- (27) Literature references for the oxidation potential of diphenylmethylamine: (a) Reference 2a. (b) Hankin, S.; Sandman, D. *J. Mol. Cryst. Liq. Cryst.* **1990**, *186*, 197. (c) Miyasaka, H.; Nagata, T.; Kiri, M.; Mataga, N. *J. Phys. Chem.* **1992**, *96*, 8060.
- (28) Literature references for the oxidation potential of *N*-methylaniline: (a) Cooper, B. E.; Owen, W. J. *J. Organomet. Chem.* **1971**, *29*, 33. (b) Reference 26d. (c) Reference 26f. (d) Yasui, S.; Tsujimoto, M.; Itoh, K.; Ohno, A. *J. Org. Chem.* **2000**, *65*, 4715. (e) Reference 11f. (f) Reference 26j. (g) Reference 26l. (h) Reference 26m. (i) Worrall, D. R.; Williams, S. L.; Wilkinson, F.; Crossley, J. E.; Bouas-Laurent, H.; Desvergne, J.-P. *J. Phys. Chem. B* **1999**, *103*, 9255. (j) Satpati, A. K.; Nath, S.; Kumbhakar, M.; Maity, D. K.; Senthilkumar, S.; Pal, H. *J. Mol. Struct.* **2008**, *878*, 84.
- (29) Literature references for the oxidation potential of 4-bromo-*N,N*-dimethylaniline: (a) Reference 26d. (b) Ahlberg, E.; Helgee, B.; Parker, V. D. *Acta Chem. Scand., Ser. B* **1980**, *34*, 187. (c) Reference 21a. (d) Kikuchi, K.; Hoshi, M.; Niwa, T.; Takahashi, Y.; Miyashi, T. *J. Phys. Chem.* **1991**, *95*, 38. (e) Reference 16u.
- (30) Literature references for the oxidation potential of *N,N*-dimethylaniline: (a) Seo, E. T.; Nelson, R. F.; Fritsch, J. M.; Marcoux, L. S.; Leedy, D. W.; Adams, R. N. *J. Am. Chem. Soc.* **1966**, *88*, 3498. (b) Reference 9c. (c) Reference 26d. (d) Anderson, C. P.; Salmon, D. J.; Meyer, T. J.; Young, R. C. *J. Am. Chem. Soc.* **1977**, *99*, 1980. (e) Bock, C. R.; Connor, J. A.; Gutierrez, A. R.; Meyer, T. J.; Whitten, D. G.; Sullivan, B. P.; Nagle, J. K. *J. Am. Chem. Soc.* **1979**, *101*, 4815. (f) Glogowski, M. E.; Williams, J. L. R. *J. Organomet. Chem.* **1981**, *218*, 137. (g) Reference 25. (h) Reference 16f. (i) Fujimori, K.; Takata, T.; Fujiwara, S.; Kikuchi, O.; Oae, S. *Tetrahedron Lett.* **1986**, *27*, 1617. (j) Reference 21a. (k) Hall, L. R.; Iwamoto, R. T.; Hanzlik, R. P. *J. Org. Chem.* **1989**, *54*, 2446. (l) Konno, A.; Fuchigami, T.; Fujita, Y.; Nonaka, T. *J. Org. Chem.* **1990**, *55*, 1952. (m) Reference 29d. (n) Reference 27c. (o) Pandey, G.; Rani, K. S.; Lakshmaiah, G. *Tetrahedron Lett.* **1992**, *33*, 5107. (p) Reference 26j. (q) Reference 9i. (r) Reference 26m. (s) Reference 28i. (t) Fabbrini, M.; Galli, C.; Gentili, P.; Macchitella, D.; Petride, H. *J. Chem. Soc., Perkin Trans. 2* **2001**, 1516. (u) Fukuzumi, S.; Ohkubo, K.; Suenobu, T.; Kato, K.; Fujitsuka, M.; Ito, O. *J. Am. Chem. Soc.* **2001**, *123*, 8459. (v) Kumbhakar, M.; Nath, S.; Mukherjee, T.; Pal, H. *J. Chem. Phys.* **2004**, *120*, 2824. (w) Reference 16q. (x) Reference 22. (y) Reference 16u. (z) Reference 28j. (aa) Hasegawa, E.; Hirose, H.; Sasaki, K.; Takizawa, S.; Seida, T.; Chiba, N. *Heterocycles* **2009**, *77*, 1147.
- (31) Literature references for the oxidation potential of acetanilide: (a) Bordwell, F. G.; Algrim, D. J.; Harrelson, J. A., Jr. *J. Am. Chem. Soc.* **1988**, *110*, 5903. (b) Brown, G. N.; Birks, J. W.; Koval, C. A. *Anal. Chem.* **1992**, *64*, 427. (c) Tadesse, M. A.; D'Annibale, A.; Galli, C.; Gentili, P.; Sergi, F. *Org. Biomol. Chem.* **2008**, *6*, 868.
- (32) Literature references for the oxidation potential of 2,2'-dimethoxybiphenyl: (a) Zweig, A.; Maurer, A. H.; Roberts, B. G. *J. Org. Chem.* **1967**, *32*, 1322. (b) Ronlan, A.; Coleman, J.; Hammerich, O.; Parker, V. D. *J. Am. Chem. Soc.* **1974**, *96*, 845.
- (33) Literature references for the oxidation potential of 4-methoxybiphenyl: (a) Reference 32a. (b) Mizuno, K.; Ichinose, N.; Tamai, T.; Otsuji, Y. *Tetrahedron Lett.* **1985**, *26*, 5823. (c) Wilkinson, F.; Abdel-Shafi, A. A. *J. Phys. Chem. A* **1997**, *101*, 5509.
- (34) Literature references for the oxidation potential of 4,4'-dimethoxybiphenyl: (a) Reference 32a. (b) Reference 32b. (c) Reference 33c. (d) Park, S. M.; Bard, A. J. *Chem. Phys. Lett.* **1976**, *38*, 257.
- (35) Literature reference for the oxidation potential of 3,3',4,4'-tetramethoxybiphenyl: ref 32b.
- (36) (a) Brown, C. J.; Corbridge, D. E. C. *Acta Crystallogr.* **1954**, *7*, 711. (b) Pederson, B. F.; Pederson, B. *Tetrahedron Lett.* **1965**, *6*, 2995. (c) Brown, C. J. *Acta Crystallogr.* **1966**, *21*, 442. (d) Pederson, B. F. *Acta Chem. Scand.* **1967**, *21*, 1415. (e) Nanjian, M. J.; Kannappan, V.; Ganesan, R. *Indian J. Chem.* **1979**, *18b*, 461. (f) Tian, Y.-Z.; Wu, Z.-W.; Sun, H.-Y.; Wang, Z.-Q. *Youji Huaxue* **1992**, *12*, 41. (g) Saito, S.; Toriumi, Y.; Tomoika, N.; Itai, A. *J. Org. Chem.* **1995**, *60*, 4715. (h) Yamasaki, R.; Tanatani, A.; Azumaya, I.; Saito, S.; Yamaguchi, K.; Kagechika, H. *Org. Lett.* **2003**, *5*, 1265. (i) Grasel, F. D. S.; Oliveira, T. C. D.; Fontoura, L. A. M.; Rigotti, I. J. D. C.; Netz, P. A. *Int. J. Quantum Chem.* **2012**, *112*, 1678.
- (37) For reviews of keto-enol cation radical tautomerizations, see: (a) Schmittel, M. *Top. Curr. Chem.* **1994**, *169*, 183. (b) Gebicki, J.; Bally, T. *Acc. Chem. Res.* **1997**, *30*, 477.
- (38) Marenich, A. V.; Olson, R. M.; Kelly, C. P.; Cramer, C. J.; Truhlar, D. G. *J. Chem. Theory Comput.* **2007**, *3*, 2011.
- (39) Winkler, F. K.; Dunitz, J. D. *J. Mol. Biol.* **1971**, *59*, 169.
- (40) (a) Consistent with the conformational interconversion proposed here, the difference between the vertical ionization potentials of *N*-methylacetanilide and acetanilide (0.35 eV^{40b}) is significantly larger than ΔE_{ox} (0.057 eV). (b) Nakagaki, R.; Kobayashi, T.; Nagakura, S. *Bull. Chem. Soc. Jpn.* **1980**, *53*, 901.
- (41) Only one neutral molecule in the training set used to parametrize SM8³⁸ contained a nitrile functional group, acetonitrile itself. The predicted solvation free energy of acetonitrile by SM8 is -6.41 kcal/mol, whereas the experimental value is -4.85 kcal/mol.
- (42) For recent attempts to calculate oxidation potentials, see: (a) Winget, P.; Weber, E. J.; Cramer, C. J.; Truhlar, D. G. *Phys. Chem. Chem. Phys.* **2000**, *2*, 1231. (b) Baik, M.-H.; Friesner, R. A. *J. Phys. Chem. A* **2002**, *106*, 7407. (c) Han, Y.-K.; Jung, J.; Cho, J.-J.; Kim, H.-J. *Chem. Phys. Lett.* **2003**, *368*, 601. (d) Fu, Y.; Liu, L.; Yu, H.-Z.; Wang, Y.-M.; Guo, Q.-X. *J. Am. Chem. Soc.* **2005**, *127*, 7227. (e) Yu, A.; Liu, Y.; Li, Z.; Cheng, J.-P. *J. Phys. Chem. A* **2007**, *111*, 9978. (f) Singh, N. K.; Shaik, M. S.; O'Malley, P. J.; Popelier, P. L. A. *Org. Biomol. Chem.* **2007**, *5*, 1739. (g) Riah, S.; Norouzi, P.; Bayandori Moghaddam, A.; Ganjali, M. R.; Karimipour, G. R.; Sharghi, H. *Chem. Phys.* **2007**, *337*, 33. (h) Alizadeh, K.; Seyyedi, S.; Shamsipur, M. *Pol. J. Chem.* **2008**, *82*, 1449. (i) Guerard, J. J.; Arey, J. S. *J. Chem. Theory Comput.* **2013**, *9*, 5046 and references therein.
- (43) Bourelande, J. L.; Gallardo, I.; Guirado, G. *J. Am. Chem. Soc.* **2007**, *129*, 2817.
- (44) (a) Pangborn, A. B.; Giardello, M. A.; Grubbs, R. H.; Rosen, R. K.; Timmers, F. J. *Organometallics* **1996**, *15*, 1518. (b) Alaimo, P. J.; Peters, D. W.; Arnold, J.; Bergman, R. G. *J. Chem. Educ.* **2001**, *78*, 64.
- (45) Dockery, K. P.; Dinnocenzo, J. P.; Farid, S.; Goodman, J. L.; Gould, I. R.; Todd, W. P. *J. Am. Chem. Soc.* **1997**, *119*, 1877.
- (46) Liu, L.; Zhang, Y.; Xin, B. *J. Org. Chem.* **2006**, *71*, 3994.
- (47) Ciana, C.-L.; Phipps, R. J.; Brandt, J. R.; Meyer, F.-M.; Gaunt, M. *J. Angew. Chem., Int. Ed.* **2011**, *50*, 458.
- (48) Lipshutz, B. H.; Butler, T.; Swift, E. *Org. Lett.* **2008**, *10*, 697.
- (49) Cheng, G.; Luo, M. *Eur. J. Org. Chem.* **2011**, 2519.
- (50) Yin, J.; Buchwald, S. L. *Org. Lett.* **2000**, *2*, 1101.
- (51) Martin, M. T.; Liu, B.; Cooley, B. E., Jr.; Eaddy, J. F. *Tetrahedron Lett.* **2007**, *48*, 2555.
- (52) *Spartan'14*; Wavefunction, Inc.: Irvine, CA, 2014.
- (53) (a) Becke, A. D. *J. Chem. Phys.* **1993**, *98*, 5648. (b) Stephens, P. J.; Devlin, F. J.; Chabalowski, C. F.; Frisch, M. J. *J. Phys. Chem.* **1994**, *98*, 11623.