Acidochromicity of Bisarylethynylbenzenes: Hydroxy versus Dialkylamino Substituents
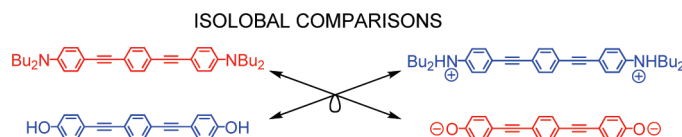
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This contribution investigates the electronic difference of dibutylamino/dibutylammonium and phenol/phenolate groups in four simple distyrylbenzenes and bisarylethynylbenzenes. The compounds and their protonated and deprotonated species, respectively, were investigated by UV−vis and emission spectroscopies. While the anilinium and phenol compounds displayed similar spectroscopic properties, this was less so the case for the comparison of the dialkylanilines with the corresponding phenolates. In this case, the hydrogen bonding ability of the phenolates distorted the results as the hydrogen donating/accepting properties of the investigated solvents have a disproportional influence on the electronic properties of the phenolates when compared to the dialkylamines. If one uses acetonitrile as solvent, these effects disappear, as acetonitrile is neither a good hydrogen bond acceptor nor a hydrogen bond donor. The results are in line with the *para*-Hammet constant for OH ($\sigma = -0.37$) being significantly smaller than that for NMe_2 substituents ($\sigma = -0.83$) and reinforces the notion that the lone pairs in these phenols are not readily available for interaction with the π-system, as they are perhaps energetically too low lying. However, in the case of the phenolates, the lone pairs do interact significantly.

Introduction

Reactive chromophores are fluorophores that change color, emission wavelength, and/or emission intensity upon exposure to analytes and are potentially useful as sensors. They contain a chromophoric π-conjugated core with an embedded functionality possessing free electron pairs before or after addition of an analyte.[1] The interaction of the free electron pairs of functional fluorophores with suitable analytes or stimuli influences the position of the HOMO, the LUMO, or both and elicits changes in absorption and emission.

The concept of isolobality of molecules was set forth by Hoffmann[2] and asserts that molecules of similar frontier molecular orbital (FMO) structure, geometry, and electron count display similar reactivity and properties. It is a qualitative model that guides the understanding of properties and reactivities of analogous molecules. One should, therefore, be able to use the isolobal principle to predict—at least qualitatively—the expected responses of classes of consanguine fluorophores toward change of pH or metal coordination. Superficially, one might expect hydroxy substituents to be isolobal to amino groups. However, a simple application of the isolobal principle will not always suffice in such organic systems, as the relative orbital ordering results in systems where (in a formal sense) free electron pairs interact predominately with either the σ- or the π-system. If the free electron pairs are energetically low lying, we expect them to interact predominately with the σ-system, while energetically higher lying electron pairs should have a larger interaction with the π-system.

A simple test bed for this hypothesis would be compounds **3a** and **4a**, bis(arylethynyl)benzenes functionalized with dibutylamino and hydroxy groups, respectively. Though

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(2) (a) Hoffmann, R. *Angew. Chem., Int. Ed. Engl.* **1982**, *21*, 711–724. (b) Evans, D. G.; Mingos, D. M. P. *J. Organomet. Chem.* **1982**, *232*, 171–191.
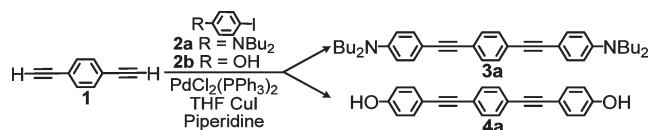
synthetically simple, their sensory responses have not been examined.[3] Comparison of **3a** and **4a** with their analogous distyrylbenzenes[4] **5a** and **6a** permits the expansion of this study to investigate differences that arise when alkenyl groups are exchanged for alkynyl groups. Probing the acidochromicity and photophysical properties of **3a**–**6a** should offer insight into the application of the isolobal principle and provide an understanding of fundamental physical−organic issues in these systems.

Results and Discussion

Distyrylbenzene compounds **5a** and **6a** were synthesized according to literature procedures.[5,6] Surprisingly, **4a**[7] has been reported only once and **3a** is unreported, although the dimethyl-[8] and dihexyl-substituted[9] compounds are known. Heck−Cassar−Sonogashira−Hagihara (HCSH) coupling of **2a** to **1** furnishes **3a**. Similarly, **4a** was synthesized from the HCSH coupling of **2b** with **1** (Scheme 1).[10] Upon protonation with trifluoroacetic acid or deprotonation with tetrabutylammonium hydroxide, compounds **3b**, **4b**, **5b**, and **6b** are obtained.

For ease of discussion, isolobal pairs have been placed into sets (**A**−**D**, Figures 1 and 2). These compounds were examined through UV−vis and fluorescence spectroscopies (dilute solutions in ethyl ether, 1,4-dioxane, chloroform, dichloromethane, methanol, ethanol, isopropanol, *tert*-butyl alcohol, acetonitrile, dimethylformamide, and dimethylsulfoxide; see Supporting Information and Figure 2). Figure 2 displays the absorption and emission of sets **A**−**D** in four representative solvents to permit a qualitative examination of solvent effects upon each compound. For simplicity, ethyl ether, methanol, acetonitrile, and dimethylsulfoxide were chosen because they represent different

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SCHEME 1. Synthesis of Compounds 3a and 4a from 1 via Sonogashira Coupling of Substituted *p*-Iodobenzenes 2a,b

classes (i.e., nonpolar, polar protic, and polar aprotic solvents). The photophysical responses of all herein investigated species were well-behaved yet interesting in these solvents. In the case of sets **C** and **D**, with the exception of **4a** in the very polar solvent DMSO, the absorption spectra for both compounds are nearly each superimposable in a range of solvents. The absorption spectra of **3b** and **4a** are only ∼10 nm apart and display similar vibronic features. Similarities are also observed in the emission spectra of set **D**; **3b** displays nearly overlapping, structured emissions in different solvents. **4a** exhibits a similarly featured emission in diethyl ether; however, as solvent polarity increases, the vibronic features give way to a broadened, smooth line shape. Once again, the emission λ_{max} of **4a** is similar to that of **3b**. Set **C** behaves in a nearly identical fashion to **D**; however, the absorption and emission spectra are red-shifted by approximately 30 and 40 nm, respectively.

In sets **C** and **D**, the chromophores lack available lone pairs; as a result, we would expect little solvent dependence in their absorption or emission λ_{max}. Furthermore, the isolobal principle suggests all four chromophores should exhibit similar photophysical properties. Indeed, this is what is observed. Surprising differences were observed in sets **A** and **B**, where the chromophores possess available lone pairs. The isolobal principle predicts that pairs **5a** and **6b** and **3a** and **4b** should exhibit similar photophysical properties; furthermore, we expect sets **A** and **B** to behave in a similar fashion. While sets **A** and **B** are similar, differences appear in the pairs **5a** and **6b** and **3a** and **4b**. In the case of dibutylamino-functionalized **5a** and **3a**, the absorption spectra in a variety of solvents are similarly featured and exhibit a minimal (∼25 nm) solvent dependence. Greater solvent dependence is observed in the emission spectra. The emission of **5a** and **3a** in ether is featured; as solvent polarity increases, the emission is red-shifted (∼60 nm) and vibronic definition disappears.

In **6b** and **4b**, methanol exhibits the highest energy absorption, and dramatic solvent dependence (∼80 nm) is observed in the absorption maxima. Divergence is also observed in the emission spectra. The emission of **6b** and **4b** in diethyl ether is considerably red-shifted relative to their alkylamino counterparts (∼80−100 nm). Little solvent dependence is observed in the emission of **6b** (∼20 nm), while in the case of **4b**, a large solvent effect is seen. Here, the emission of **4b** varies by more than 150 nm, ranging from MeOH at highest energy to ether at lowest energy.

The compounds in sets **C** and **D** behave as isolobal pairs; however, the suprising lack of "isolobality" in the case of **A** and **B** requires an explanation. Previously, we have analyzed solvent-dependent absorption and emission spectra of similar compounds utilizing the Lippert−Mataga equation.[6a] A solvent's dielectric constant and refractive index are used to calculate an orientation polarizability value (Δf) for a given solvent; Δf is then plotted against the energy of the Stokes
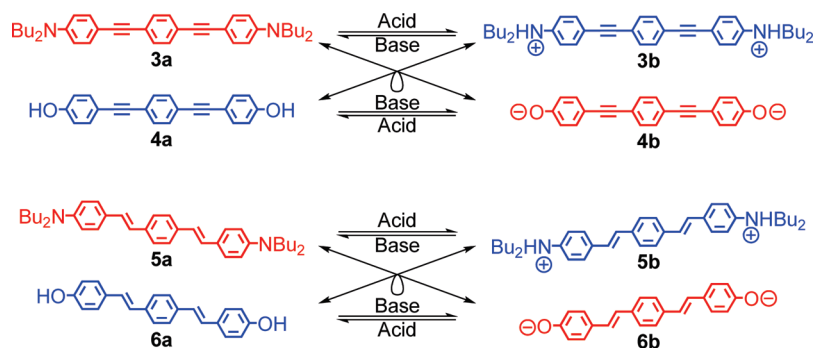
FIGURE 1. Acid/base equilibrium relationships of **3a−6b** are shown. Diagonal isolobal relationships are indicated.
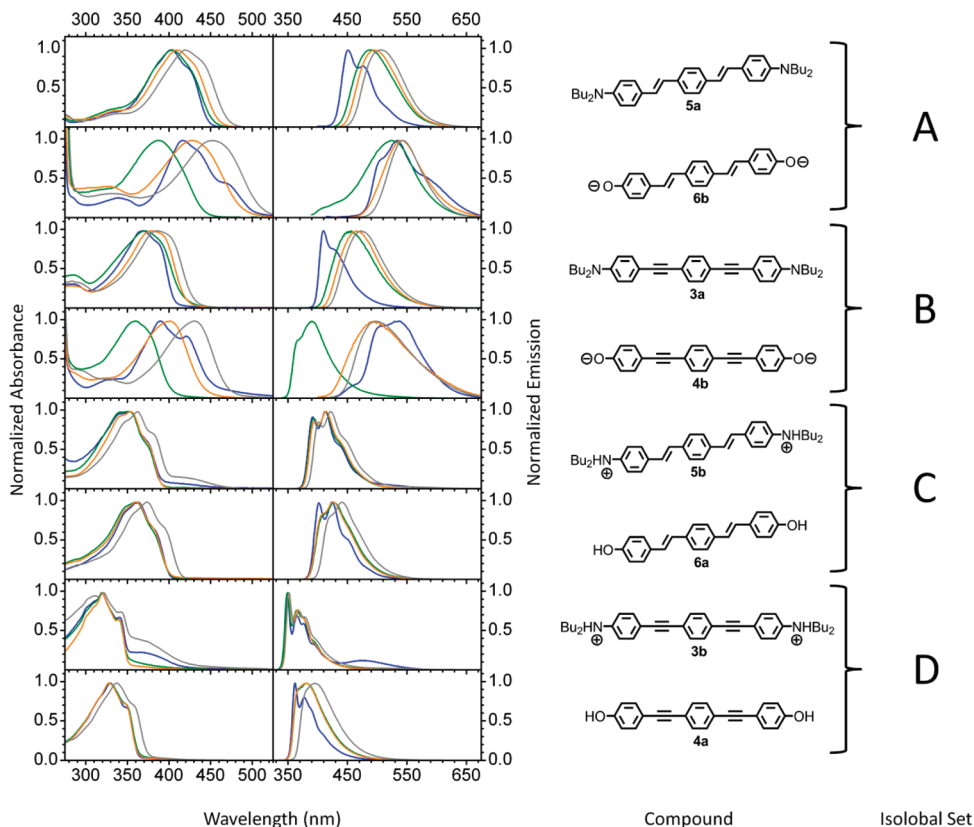

FIGURE 2. Absorption (left) and emission (right) spectra of **3a−6b** in ethyl ether (blue), methanol (green), acetonitrile (orange), and dimethylsulfoxide (gray). Compounds are grouped by electronic structure into isolobal sets **A−D** (far right).

shift for each measured solvent.[11] Generally, a linear plot is obtained with the magnitude of the slope reflecting the change in a fluorophore's dipole moment upon excitation.

A Lippert−Mataga analysis of **3a−6b** proved difficult; whereas the dibutylamino compounds (**3a**, **3b**, **5a**, and **5b**) were well correlated, the phenolic compounds (**4a**, **4b**, **6a**, and **6b**) showed no meaningful relationship. The Lippert−Mataga equation only considers nonspecific effects related to solvent reorganization. Solvent−fluorophore interactions may, however, play a critical role in understanding the behavior of the phenolates.

We subjected **3a−6b** to a Kamlet−Taft (KT) solvent analysis accounting for solvent-specific interactions due to

hydrogen bonding or acid/base reactions.[12] KT relies on a multivariate linear regression analysis of the absorption λ_{max} of a chromophore in a variety of solvents (eq 1).

Kamlet−Taft multivariate approach :

$$\nu(1000/cm) = \nu_0 + s\pi^* + a\alpha + b\beta \qquad (1)$$

The KT approach correlates the solvent-dependent spectral shifts observed (ν) for a chromophore with three solvent-dependent parameters (α, β, and π^*). Here, ν_0

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TABLE 1. Coefficient Values Obtained from Kamlet−Taft Analysis

	A		B		C		D	
compound	**5a**	**6b**	**3a**	**4b**	**5b**	**6a**	**3b**	**4a**
$\nu_0{}^a$	25.1	25.4	27.4	26.8	28.8	27.9	31.2	30.7
s	−1.2	−1.4	−1.5	−2.5	−0.76	−0.76	−0.26	−0.52
a	0.29	2.7	0.17	2.9	0.60	0.52	−0.07	0.32
b	0.16	−2.7	0.14	−1.5	−0.63	−0.31	0.30	−0.55
R^b	0.95	0.90	0.95	0.80	0.83	0.77	0.58	0.80

^{a}Units of ν_0 are in 10^3 cm^{-1}. $^b R$ is the correlation coefficient.

corresponds to the projected absorption or emission energy of the chromophore in a vacuum, while s, a, and b are fitted coefficients obtained from the linear regression analysis (see Supporting Information). The index π^* expresses the ability of the solvent to stabilize the chromophore's charge and/or dipole via nonspecific dielectric interactions, while α and β incorporate solvent−solute interactions; β describes the proton accepting character of the solvent, while α corresponds to the hydrogen donating character of the solvent. By analyzing the coefficients, it is possible to determine the degree to which each mode of interaction (α, β, and π^*) affects the absorption λ_{max} of a chromophore.

Table 1 shows the results of the Kamlet−Taft analysis. The calculated ν_0 values range from 25.1 to 31.2×10^3 cm^{-1}; the compounds within isolobal set **A** have similar ν_0 values as do those in sets **B**, **C**, and **D**. As one would expect, the values of ν_0 for the styryl isolobal set **A** are slightly lower, indicating a red shift in the gas phase absorption relative to their arylethynyl congeners in set **B**. The red shift is a consequence of the hybridization change (sp → sp^2) in the bridge carbons when going from alkynes to alkenes. This more electron-rich system allows the phenyl groups to interact somewhat more strongly through the conjugative bridge. The same relationship holds true for the styryl compounds in **C** relative to their arylethynyl analogues in **D**.

The s coefficient of the π^* term reflects the contribution of nonspecific dielectric interactions of the solvent with the fluorophore and is somewhat analogous to the slope obtained from a Lippert−Mataga analysis; it is related to the fluorophore's dipole. In all cases, this term is negative, inducing a spectral red shift. Isolobal pairs behave similarly and as we would expect. In sets **C** and **D**, electron pairs are involved in proton bonding. As a consequence, s is less significant, suggesting a smaller dipole. In sets **A** and **B**, where free electron pairs are more available, s is larger, suggesting a greater dipole.

The a and b coefficients for the isolobal sets **C** and **D** are modest. The lack of available free electron pairs results in minimal solvent-specific interaction. Similarly, in the case of dibutylamino compounds **3a** and **5a**, the a and b values are also relatively small. The s term is the predominant influence on the observed absorption. However, in the case of the deprotonated phenols **4b** and **6b**, a and b become significant, with a inducing a hypsochromic shift and b resulting in a bathochromic shift. This results in the divergent photophysical behavior observed in **4b** and **6b** relative to their isolobal counterparts.

Why is this pronounced solvent effect observed exclusively in **4b** and **6b** and not in their isolobal counterparts **3a**

and **5a**? One might attribute this differential behavior to the increased basicity of a phenolate (p$K_a \sim 10$)^{13} as compared to a dialkylamino group (p$K_a \sim 6.6$).^{1} A look into the Hammett σ values^{14} is instructive, as here the σ values of −O$^-$, −N(C$_3$H$_7$)$_2$, −OH, and −NMe$_2$H$^+$ are −0.81, −0.93, −0.37, and 0.70, respectively.^{15} The Hammett values testify to the apparent electronic similarity of the phenolate to the dialkylamino groups but of course do not take into account the hydrogen bonding contributions that will be stronger in the case of a phenolate than in a neutral amine. More surprising is the similarity of the spectroscopic properties of the phenols and the ammonium salts (where hydrogen bonding apparently does not play a significant role), given the larger differences in their respective Hammett parameters. While the correlation with Hammet σ_p parameters is appealing and grossly correct, they clearly cannot explain the subtleties in this interesting system.

An important additional point is the quantum yields of these eight compounds, which we determined in acetonitrile. Generally, in the pairs **A** and **B**, the aniline always has a significantly higher quantum yield than the phenolate. In the case of **4b**, the quantum yield is below 0.01. For the pairs **C** and **D**, the differences are much smaller and the quantum yields are generally quite substantial. In both cases, the ammonium species display a higher quantum yield than the phenols. The reason for the differences in the quantum yields is somewhat obscure, and the only rough trend is that the higher the emission wavelength, the lower the emission quantum yield is; a notable exception is **4b** with its vanishing emission. Generally, the amines do better with respect to emission quantum yield than the phenols and phenolates, for subtle reasons that are not easily divined.

Conclusions

We examined the photophysical properties and acidochromicity of hydroxy- and dibutylamino-functionalized distyrylbenzenes and arylethynylbenzenes. While sets **C** and **D** (Figure 2) exhibit similar photophysical behavior as expected and do not possess effective lone pairs, sets **A** and **B** (Figure 2)—possessing lone pairs that interact effectively with the π-system of the fluorophore—show different behavior in absorption and emission. These differences stem from fluorophore−solvent interactions, which disproportionally affect the phenolate-substituted dyes.

The true electronic similarity of **3a−6b** can be appreciated when viewing their absorption and emission in acetonitrile—a solvent possessing small and similar α and β parameters (Figure 3 and Table 2). The contribution of solute-specific effects is minimized; the isolobal similarity of **A** and **B** as well as **C** and **D** becomes readily apparent. The phenolate and dibutylamino groups are isolobal despite the difference in their pK_a values and the presence of the ionic phenolate. However, they behave quite differently in practice, particularly in hydrogen bonding solvents.

Interesting and somewhat unexpected is the finding that free electron pairs in the hydroxy compounds **4a** and **6a** are *not* available for conjugation with the π-system. Apparently,

(13) For comparison, the pK_a values of methanol and ethanol are 15.5 and 16.0, respectively. Additional pK_a values for the solvents used in this study are listed in the Supporting Information.

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(15) Interpolated from the σ_p values for −NH$_3{}^+$ (0.60) and NMe$_3{}^+$ (0.82); the other values are directly from Table 1 in ref 14b.
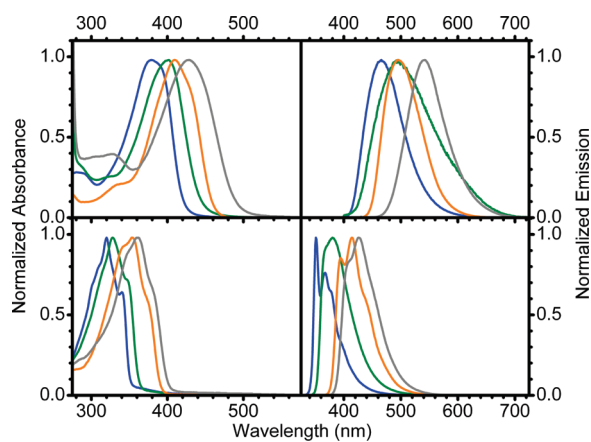
FIGURE 3. Absorption (left) and emission (right) spectra of **3a**−**6b** in acetonitrile. Top: **3a** (blue), **4b** (green), **5a** (orange), **6b** (gray). Bottom: **3b** (blue), **4a** (green), **5b** (orange), **6a** (gray).

these electrons are too low in energy to permit efficient interaction. The other, somewhat expected trend is that dyes containing alkene bridges display red-shifted spectral features when compared to analogous fluorophores featuring alkyne groups. We note that the change hybridization (sp → sp^2) increases the intrinsic electron donating character of the distyryl compounds as compared to the bisarylethynyl compounds. A red shift in ν_0 results. While the gas phase absorption, ν_0, is red-shifted in all of the alkene compounds relative to the corresponding alkyne compounds, the degree

TABLE 2. Selected Photophysical Data of Compounds 3a−6b in CH$_3$CN

	A		**B**		**C**		**D**	
compound	**5a**	**6b**	**3a**	**4b**	**5b**	**6a**	**3b**	**4a**
λ_{max} absorption (nm)	410	431	378	408	353	364	321	328
λ_{max} emission (nm)	494	542	466	496	414	426	351	380
ε (M$^{-1}\cdot$cm^{-1})	7774	17515	6799	9632	4712	24191	6089	10230
Φ	0.60[a]	0.13	0.51	< 0.01	0.73[a]	0.43	0.54	0.43

[a]Previously reported in ref 4a.

to which a solvent effects the absorption of a molecule is nearly identical among an alkene−alkyne pair as can be seen through similar values of *s*, *a*, and *b*. From the above, we therefore would recommend acetonitrile as the preferred solvent for the comparison of a series of consanguine fluorophores. In addition, our study gives design guidelines as how to engineer absorption and emission wavelengths in bisstyrylbenzene and bisarylethynylbenzene-like dyes.

Supporting Information Available: Additional figures and methods. This material is available free of charge via the Internet at http://pubs.acs.org.