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is good evidence for the hypothesis that, if a fixed origin calculation is performed, then the origin should be chosen at the center of mass. For NHDT, the accuracy of the calculated value of the axial atomic tensor for the nitrogen atom decreases more rapidly than that for the hydrogen as the distance of each atom from the origin is increased.<sup>13</sup> This conclusion is borne out by the good agreement obtained for the methylthiirane VCD spectra by fixing the origin at the center of mass.

The sensitivity of the choice of gauge is a troubling feature of the calculation of VCD spectra. As the quality of the basis sets used increases, this dependence should diminish. However, our preliminary calculations of rotational strengths of methylthiirane for selected normal modes using the larger  $6-31G^{**}$  basis set gave essentially the same results as those obtained by using the  $6-31G^{**}$ set. At this time, it is impracticable to use basis sets routinely that are much larger than the  $6-31G^{**}$  basis for molecules as large or larger than methylthiirane. Consequently, a more detailed theoretical analysis of the choice of gauge is required.

Inaccuracies in calculated VCD spectra arise from inaccuracies in the force field, the atomic polar tensors, and the atomic axial tensors. Results of calculations for the molecule thiirene indicate that atomic polar tensors may not be calculated very accurately even at a post-SCF level. Extremely accurate SCF and post-SCF calculations (DZP-CISD) have been performed on this molecule.<sup>15</sup> The improvement in the force field achieved by performing the DZP-CISD calculation rather than one at the SCF level was considerable, but the intensities did not show nearly the same degree of improvement and discrepancies with experiment remained.<sup>15</sup> Since atomic axial tensors may be even less accurate than the atomic polar tensors, the above results indicate that, while the SQM force fields are probably sufficiently accurate for VCD calculations, improvements in methods of calculating atomic polar and axial tensors may be needed in order to reproduce the details of experimental VCD spectra.

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# **Fluorescence Properties of 2,3-Diarylindenes**

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The absorbance and fluorescence properties of three 2,3-diarylindenes substituted with donor and acceptor functions were studied and compared with the corresponding donor/acceptor-substituted stilbenes. The parent systems, 2-phenyl-3-(4methoxyphenyl)-6-methoxyindene (1c) and 4-methoxystilbene (2c), show absorption and emission spectra typical for stilbene systems. Relative to the stilbene 2c, absorbance of indene 1c shows a small bathochromic shift (1500 cm<sup>-1</sup>) and a somewhat larger Stokes shift (7000 versus 5000 cm<sup>-1</sup>); neither absorbance nor emission shows much solvent sensitivity. The meta-substituted systems 2-(3-nitrophenyl)-3-(4-methoxyphenyl)-6-methoxyindene (1b) and 4'-methoxy-3-nitrostilbene (2b) both show absorbances having little solvent dependence that are shifted ca. 1200 cm<sup>-1</sup> relative to the unsubstituted analogues (1c and 2c); however, their fluorescence spectra are now very solvent sensitive, with Stokes shifts for both systems ranging from ca. 11 000  $\rm cm^{-1}$ in cyclohexane to ca. 16000 cm<sup>-1</sup> in chloroform. The very large Stokes shift of 1b and 2b can best be explained by the emission arising from a twisted intramolecular charge-transfer (TICT) state, in which the two  $\pi$  systems are mutually perpendicular, with complete charge transfer from donor to acceptor. In addition to this TICT band, the indene system 1b also shows a shorter wavelength emission that is ascribed to a locally excited state (LE). The relative intensities of the dual-emission (LE and TICT) bands of this are very solvent dependent. The absence of an LE band in the stilbene 2b suggests that it can access the twisted conformation required for the TICT state more readily than can the diarlyindene 1b. The para-substituted systems 2-(4-nitrophenyl)-3-(4-methoxyphenyl)-6-methoxyindene (1a) and 4'-methoxy-4-nitrostilbene (2a) show absorbancebands shifted bathochromically by  $5000-6000 \text{ cm}^{-1}$  relative to the unsubstituted systems 1c and 2c. The Stokes shift is again very solvent dependent but is smaller than for the para-substituted systems, in the range 5500-9000 cm<sup>-1</sup> for **1a** and 8000-12000 $cm^{-1}$  for 2a, consistent with emission from a simple intramolecular charge-transfer state (ICT) involving a more planar system having only partial charge separation. The greater Stokes shift of the stilbene 2a relative to the indene 1a may be due to the greater planarity of the stilbene system. The relative emission intensities of the indene systems varies p-NO<sub>2</sub> > H > m-NO<sub>2</sub>, that of stilbenes H > p-NO<sub>2</sub> > m-NO<sub>2</sub>, consistent with the forbidden nature of the TICT, with the indenes **1a** and 1b being far more intense than the corresponding stilbenes. The donor/acceptor-substituted 2,3-diarylindene systems provide interesting structure-dependent fluorescence characteristics that may be exploitable in biological applications.

## Introduction

The utility of fluorophores as molecular probes is based on the sensitivity of their emissive behavior (wavelength, quantum yield, polarization, and lifetime) to the environment.<sup>1</sup> This characteristic enables one to distinguish fluorophores that have been localized

in different environments, such as different subcellular compartments<sup>2</sup> or those that are bound to macromolecules versus free in solution.<sup>3</sup>

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SCHEME I







In the course of the development of 2-arylindenes<sup>4</sup> as fluorescent ligands for the estrogen receptor,<sup>5</sup> dimethoxynitroindene 1a was



found to display fluorescence of high solvatochromic character. To understand the structural basis of this solvatochromism, we compared the steady-state photophysical properties of stilbene congeners 1a-c and 2a-c. An analysis of structural and solvent effects on the absorption and emission of these stilbene systems is presented.

## **Results and Discussion**

Synthesis. The nitroindenes **1a** and **1b** were constructed in three steps: (1) acylation of anisole with 3- or 4-nitrophenylacetic acid to provide a nitrodeoxybenzoin; (2) 3-methoxybenzylation of the

TABLE I: Absorption Properties (Lowest Energy  $\pi \rightarrow \pi^*$  Band) of Donor-Only Systems 1c and 2c

		1c			2c		
solvent	$\lambda_{abs}, \\ nm$	$cm^{\nu_{abs}}$	e	λ <sub>abs</sub> , nm	$v_{abs}, cm^{-1}$	é	
cyclohexane	318	31 450	19 400	304	32 900	25 800	
EtOAc	318	31 450	20 000	304	32 900	27 700	
CH <sub>3</sub> CN	316	31650	18 400	304	32900	31 000	
EtOH	318	31 4 50	19600	304	32 900	27 800	

TABLE II:	Fluorescence	Properties	of Donor-Only	Systems	1c and
2c		-	•	•	

		1c			2c		
solvent	λ <sub>em</sub> , nm	v <sub>abs</sub> , cm <sup>-1</sup>	Stokes shift, cm <sup>-1</sup>	λ <sub>em</sub> , nm	v <sub>abs</sub> , cm <sup>−1</sup>	Stokes shift, cm <sup>-1</sup>	
cyclohexane	405	24 690	6760	361	27 700	5200	
EtOAc	412	24 270	7180	357	28 0 1 0	4890	
CH <sub>3</sub> CN	410	24 390	7260	357	28 010	4890	
EtOH	420	23 810	7640	354	28 250	4650	



Figure 1. Thermal ellipsoid representation of 2,3-bis(4-methoxyphenyl)-6-methoxyindene and accompanying diagram describing the normalized torsional angles of the three aryl rings with respect to the double bond.

nitrodeoxybenzoin enolate; (3) cyclodehydration. The 4-nitrostilbene **2a** was prepared by the hydride reduction and dehydration of the 4-nitrodeoxybenzoin **4a** (Scheme I). The 3-nitrostilbene **2b** was prepared by condensation-decarboxylation of *p*-anisaldehyde and 3-nitrophenylacetic acid<sup>6</sup> (Scheme II). The synthesis of dimethoxyindene **1c** will be described elsewhere;<sup>4e</sup> methoxystilbene **2c** is commercially available.

Absorption and Fluorescence Properties. Donor-Only Systems Ic and 2c. The absorption maximum of the dimethoxyindene Ic is bathochromically shifted about  $1500 \text{ cm}^{-1}$  relative to stilbene 2c, but with a decrease in the extinction coefficient (see Table I). These properties are due to a combination of steric perturbation of the *trans*-stilbene chromophore<sup>7</sup> by the 3-aryl substituent, which decreases the absorptivity, and a substituent effect on the double bond,<sup>8</sup> which produces the bathochromic shift.

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The crystal structure of trans-stilbene indicates essentially a planar molecule,<sup>9</sup> whereas 2,3-diarylindenes are considerably less planar (see Figure 1 for a crystallographic structure of an analogue of 1c).<sup>4d</sup> In cyclohexane, there is less vibronic structure in the absorption spectrum of indene 1c, as compared to stilbene 2c (Figure 2A), consistent with a more inhomogeneous mixture of ground-state conformers for the former.<sup>10</sup> The absorption bandwidth of the indene is larger as well, indicating greater libration about the equilibrium aryl-double bond torsional angle<sup>11</sup> or contributions from the overlapping cisoid-stilbene chromophore.

Conversely, in the fluorescence spectra, the indene shows better resolved vibronic structure than the stilbene, with a vibrational interval of 1400 cm<sup>-1</sup>, in accord with a C==C stretch mode<sup>10</sup> (Figure 2B). Thus, a mirror-image relationship does not exist between the absorption and fluorescence spectra of either compound, demonstrating a difference in molecular geometry between the equilibrium ground state and the equilibrium excited state.<sup>12</sup>

The larger Stokes shift of the indene as compared to the stilbene (Table II) indicates that a more substantial relaxation process is occurring between the Franck-Condon excited state and the equilibrium exicted state (the state from which emission is observed).<sup>13</sup> Neither the absorption nor emission wavelengths of either compound are appreciably affected by solvent polarity, so only a weak excited-state dipole moment exists.<sup>14</sup> Thus, solvent relaxation is minimal, and the Stokes shift is principally due to significant geometric relaxation, in excess of the usual vibrational relaxation of organic molecules of about 1500  $\rm cm^{-1}.^{15}$  . In the excited state, the  $\pi$ -bond orders will be reversed, and the steric strain of the indene in the ground state will be relieved by the lengthening of the double bond.<sup>10</sup>

The fluorescence quantum yield of a similar indene system, 2,3-diphenyl-6-methoxyindene (6), was determined to be 0.15 in



ethanol,<sup>4d</sup> significantly higher than *trans*-stilbene ( $\Phi_{\rm F} = 0.05$ )<sup>16</sup> or triphenylethylene (very small in fluid solutions).<sup>17</sup> trans-Stilbene has deactivation pathways available, such as isomerization and low-frequency torsional vibrations,<sup>18</sup> that are unavailable to the indene because of its cyclic structure. Triphenylethylene has a nonplanar propeller-like structure,<sup>19</sup> in which photocyclization becomes a dominant deactivation pathway in fluid solutions.<sup>17</sup> However, the quantum yield of indene 6 is much lower than that of the rigid indene 7 ( $\Phi_F = 1$ )<sup>20</sup> or 2-phenylindene (8,  $\Phi_F = 0.78$ ).<sup>21</sup>

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TABLE III: Absorbance Characteristics (Lowest Energy Band) of 1b and 2b

	1b			2b		
solvent	λ <sub>abs</sub> , nm	$v_{abs}, cm^{-1}$	e	$\lambda_{abs}, \\ nm$	$v_{abs}, cm^{-1}$	é
cyclohexane	332	30120	14800	318	31 450	27 600
CCl₄	334	29 940	16 500	322	31 060	26100
benzene	336	29 760	16 500	322	31 060	24 800
ether	330	30 300	19 200	318	31 450	26 900
dioxane	330	30 300	18 200	320	31 250	22800
THF	332	30120	18 600	322	31 060	28 800
EtOAc	330	30 300	18 000	320	31 250	28 100
CHCl <sub>3</sub>	332	30120	16700	322	31 060	28 900
CH <sub>2</sub> Cl <sub>2</sub>	330	30 300	14100	322	31 060	28 700
acetone	330 <sup>a</sup>	30 300	а	320ª	31 250	а
CH3CN	326	30 670	16 400	318	31 450	29 700
n-BuOH	332	30120	16 200	320	31 250	26100
EtOH	330	30 300	16 900	320	31 250	29 200

<sup>a</sup>Too close to the UV cutoff of the solvent for accurate measurement.

**TABLE IV: Emission Characteristics of 1b** 

	emission								
solvent	λ <sub>B</sub> ,ª nm	$v_{\rm B},  {\rm cm}^{-1}$	λ <sub>A</sub> ,ª nm	$\nu_{\rm A},{\rm cm}^{-1}$	Stokes shift, A band,cm <sup>-1</sup>				
cyclohexane	425	23 530	510	19610	10510				
CCl₄	b	b	570	17 540	12400				
benzene	420	23810	578	17 300	12460				
ether	421	23750	565	17 700	12600				
dioxane	422	23 700	601	16640	13660				
THF	437	22880	607	16470	13650				
EtOAc	424	23 580	620	16130	14170				
CHCl <sub>3</sub>	423	23 640	690	14 490	15630				
CH <sub>2</sub> Cl <sub>2</sub>	425	23 530	b	b	с				
acetone	420	23810	Ь	b	С				
ethanol	420	23 810	Ь	Ь	с				

<sup>a</sup> Dual fluorescence is observed for this compound. For the definition of A and B bands, see the text. <sup>b</sup> Not observed. <sup>c</sup> Not applicable.

TABLE V: Emission Characteristics of 2b

	emission					
solvent	λ <sub>em</sub> , nm	$\nu_{\rm em},  {\rm cm}^{-1}$	Stokes shift, cm <sup>-1</sup>			
cyclohexane	504	19840	11610			
ČCl₄	510	19610	11 450			
benzene	532	18 800	12260			
ether	518	19310	12140			
dioxane	570	17 540	13710			
THF	576	17 360	13 700			
EtOAc	596	16780	14 470			
CHCl <sub>3</sub>	640	15630	15430			
CH <sub>2</sub> Cl <sub>2</sub>	666	15020	16040			
acetone	690	14490	16760			

In regard to the latter comparison, 6 has a lower quantum yield because of its less planar conformation<sup>22</sup> or because the cisoidstilbene unit obscures an obvious long-axis transition moment. A similar argument can be invoked to explain the lower  $\Phi_{\rm F}$  of phenanthrene as compared to anthracene.23

The donor-only 2,3-diarylindenes show properties at room temperature consistent with both *cis*-stilbenes (photocyclization) and trans-stilbenes (fluorescence). The photocyclization of 2,3diarylindenes has been previously described.<sup>24</sup> The competition

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Figure 2. (A) Comparison of absorption spectra of 1c and 2c in cyclohexane. (B) Comparison of fluorescence spectra of 1c and 2c in cyclohexane.

between photocyclization, fluorescence, and isomerization of *cis*and *trans*-stilbenes has been extensively studied at low temperature.<sup>25</sup> Studies of the 2,3-diarylindenes may permit evaluation of the photocyclization/fluorescence competition in a single structural manifold, without the addition complication of cis-trans isomerization.

Meta-Substituted Systems 1b and 2b. The absorbance characteristics of indene 1b and stilbene 2b are shown in Table 111. In each case, the m-NO<sub>2</sub> group produces a bathochromic shift of 1200 cm<sup>-1</sup> of the lowest energy and of the donor-only systems, similar to the effect of electron-withdrawing substituents on benzene.<sup>26</sup> For both compounds, the position of the absorption maxima is not very solvent sensitive.

However, for both **1b** and **2b**, the emission maxima are extremely solvent dependent (Tables IV and V), indicative of a large dipole moment in the excited state. The large dipole moment causes solvent reorientation, with the more polar solvent stabilizing the exicted state more effectively, thereby producing a large Stokes shift.<sup>15</sup> The extremely large and solvent-dependent Stokes losses observed for both compounds suggest emission from a twisted intramolecular charge-transfer (TICT) state.<sup>27</sup> The TICT state is composed of mutually perpendicular  $\pi$  systems in which complete electron transfer has occurred, i.e., an intramolecular radical cation-radical anion pair exists.<sup>28</sup>

In 1b (but not 2b), dual fluorescence is observed. In addition to the red-shifted, solvent-sensitive A band, a higher energy B





Figure 3. Kinetic scheme for the dual fluorescence observed in indene 1b. GS, LE, and TICT refer to the ground, locally excited, and twisted intramolecular charge-transfer states, respectively. The subscripts f and o refer to fluorescence and radiationless decay, respectively.

band, arising from a locally excited (LE) state, is present. The B and is virtually solvent independent, except in THF (presumably a special solvent effect<sup>15</sup>). The position of the B band is similar to that of the solvent-insensitive emission from the donor-only indene **1c**. In ethyl acetate, the excitation bands for both the high-energy B band and the low-energy A band are similar. In  $CCl_4$ , the B band is quenched to a greater extent than the A band, consistent with the previously observed susceptibility of the LE state to quenching by external heavy-atom perturbers.<sup>28</sup> On the basis of the assignments of emissions from both LE and TICT states, which have a common origin, the kinetic scheme of Figure 3 is invoked.<sup>27</sup>

The dual fluorescence of **1b** has several interesting features. This is the first example of the TICT state observed in a compound with a methoxy/nitro donor/acceptor pair. The energy of a TICT state is given by eq  $1.^{27}$ 

$$E(\text{TICT}) = IP(D) - EA(A) + C + \Delta E_{\text{solv}}$$
(1)

IP(D) is the ionization potential of the donor, EA(A) is the electron affinity of the acceptor, C is the Coulombic attraction term, and  $\Delta E_{solv}$  is the solvation energy. If the IP(D) is too high, the TICT state does not form. For example, 9 shows TICT



emission, but 10 does not.<sup>30</sup> The respective ionization energies for the Me<sub>2</sub>N and H<sub>2</sub>N groups are 7.9 and 9.0 eV.<sup>31</sup> The ionization energy of a methoxy group is even higher (10 eV) than that of the amine.<sup>31</sup> In addition, the acceptor group cannot be too strong. In 11, the initially formed, highly polar excited state is stable; there is not much additional stabilization by TICT formation.<sup>27b</sup> Apparently, in indene 1b and stilbene 2b, the combination of a very weak donor and a very strong acceptor creates a situation in which a TICT state can be formed.

There appear to be dimensional limitations on the TICT phenomenon, because of the Coulombic term dependence. Although 9 shows the TICT emission, the corresponding extended system 12 does not.<sup>32</sup> Thus, 1b and 2b are the first stilbene



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Figure 4. Dual fluorescence of 1b in the indicated solvents. No LE band is observed in CCl<sub>4</sub>.

systems to display TICT fluorescence,<sup>33</sup> because of the lesser distance of a meta acceptor compared to a para acceptor, the stronger acceptor properties of a nitro group compared to a nitrile, or the absence of a polar, low-energy excited state, as exists for 12.32

In many cases the emergence of a TICT state is highly solvent dependent, occurring only in higher polarity solvents.<sup>27b,34</sup> In 2b, the TICT state is apparent even in cyclohexane. In all the solvents studied except cyclohexane, the TICT band is well separated from the LE band (see Figure 4). Deconvolution techniques are not necessary to dissect out each component from a composite LE-TICT band.35

The donor is involved in the rotational process to form the TICT state. Compound 13, in which the donor is held planar, does not



give the A-band emission. However, in 14, in which the acceptor is rigidified, TICT fluorescence is still observed.<sup>36</sup> In cases of a poor donor, such as the H<sub>2</sub>N group in 15, a low-energy TICT state is unlikely to be formed by donor rotation. Thus, the entire aniline moiety rotates to produce the TICT state.<sup>35</sup> However, in 1b the donor is even weaker, and the para-anisyl unit is immobilized by ring fusion. This suggests either that the nitro group or the nitrophenyl group must rotate to provide the TICT state. Two approaches may be taken to resolve this issue. Rigid systems, such as 16 and 17, may be analyzed for TICT emission, or the



influence of viscosity on the rate of TICT formation<sup>36</sup> may distinguish a small, rotating methoxy or nitro group from the large nitrophenyl group.



Figure 5. Emission spectra of 1b and 2b in EtOAc. Dual fluorescence is observed for 1b only.

TABLE VI: Absorbance Characteristics (Lowest Energy Band) of 1a and 2a

	1a			2a		
solvent	λ <sub>abs</sub> , nm	$v_{abs},$ cm <sup>-1</sup>	έ	λ <sub>abs</sub> , nm	$v_{abs}, cm^{-1}$	£
cyclohexane	396	25 250	18 600	358	27 930	21 500
ČCl₄	400	25 000	16 600	360	27 780	19 200
benzene	404	24 7 50	15000	366	27 320	18 400
ether	396	25 250	16412	358	27 930	22 800
dioxane	400	25 000	15 500	364	27 470	21 000
THF	404	24 7 50	15 400	366	27 320	20 900
EtOAc	400	25 000	16 200	366	27 320	21 500
CHCl <sub>3</sub>	408	24 510	14 500	368	27170	19 300
CH <sub>2</sub> Cl <sub>2</sub>	408	24 510	15700	370	27 030	20 200
acetone	402	24 880	16 500	364	27 470	20 300
CH <sub>3</sub> CN	402	24880	15 500	366	27 320	20 900
n-BuOH	404	24750	15000	364	27 470	19 300
EtOH	402	24 880	15 500	364	27 470	20 700

TABLE VII: Emission Characteristics of 1a and 2a

	<b>1a</b>			2a			
solvent	λ <sub>em</sub> , nm	ν <sub>em</sub> , cm <sup>-1</sup>	Stokes shift, cm <sup>-1</sup>	λ <sub>em</sub> , nm	$\nu_{em},$ cm <sup>-1</sup>	Stokes shift, cm <sup>-1</sup>	
cyclohexane	507	19720	5530	497	20120	7810	
ĊCl₄	515	19 4 20	5580	494	20 240	7540	
benzene	536	18 660	6090	494	20 240	7080	
ether	520	19230	6020	495	20 200	7730	
dioxane	559	17890	7110	503	19880	7590	
THF	570	17 540	7210	524	19 080	8240	
EtOAc	569	17 570	7430	520	19 2 30	8090	
CHCl <sub>3</sub>	631	15850	8660	579	17 270	9900	
CH <sub>2</sub> Cl <sub>2</sub>	634	15770	8740	590	16950	10080	
acetone	618	18 180	8870	594	16840	10480	
CH <sub>3</sub> CN	660	15150	9730	647	15 460	11860	
n-BuOH	612	16 340	8410	625	16 000	11470	
EtOH	625	16000	8880	645	15 500	11970	

Pretwisting in the ground state favors TICT emission over that of the LE state.<sup>27b</sup> For example, 18 has a greater TICT state



quantum yield than 9.38 Thus, the absence of an LE state in the planar stilbene 2b and its presence in the twisted indene 1b at first seems anomalous (see Figure 5). However, previous results from our lab have suggested that ring rotation in the 2,3-diarylindene system is correlated.<sup>1d</sup> Even though the two-ring is pretwisted

<sup>(34)</sup> However, TICT formation can occur in hydrocarbon solvents or even

<sup>the gas phase for certain compounds; see ref 27b.
(35) Rettig, W.; Chandross, E. A. J. Am. Chem. Soc. 1985, 107, 5617.
(36) Grabowski, Z. R.; Dobkowski, J.; Kühnle, W. J. Mol. Struct. 1984,</sup> 114,93

<sup>(37)</sup> Rettig, W. J. Phys. Chem. 1982, 86, 1970.

<sup>(38)</sup> Rotkiewicz, K.; Rubasewska, W. J. Luminesc. 1982, 27, 221.

TABLE	VIII:	Relative	Fluorescence	Intensities

compd	state <sup>a</sup>	class	benzene	dioxane	EtOAc	CH <sub>3</sub> CN
1a	QPICT	indene	$5.85 \times 10^{4}$	$6.24 \times 10^{4}$	$6.86 \times 10^{3}$	9.99
2a	PICT	stilbene	526	19.7	107	6.55
1b	TICT	indene	39.0	19.2	139	Ь
2b	TICT	stilbene	1	3.13	2.63	b
1c	LE	indene	С	С	531	С
2c	LE	stilbene	С	С	419	с

<sup>a</sup> Designation of equilibrium excited state (see text). <sup>b</sup>Unable to be observed. <sup>c</sup>Not determined.

about 27° in 1b (assuming a conformation of 1b as in Figure 1). the condition of correlated rotation requires that both the C-2-ring and the C-3-ring rotate to a position perpendicular to the donor ring prior to TICT emission. Thus, the total angular gap to be crossed by the rotation of both the 2- and 3-rings in 1b is greater than in that required by twisting only one ring in 2b, despite the greater ground-state twist angle in 1b. Hence, the TICT/LE ratio for 1b is lower than for 2b.

Para-Substituted Systems 1a and 2a. The lowest energy absorption bands of indene 1a and stilbene 2a are shifted about 500-6000 cm<sup>-1</sup> relative to the donor-only systems and are not very sensitive to solvent polarity (Table VI).

In contrast, the fluorescence spectra of 1a and 2a are very solvent dependent, with a marked red shift in the band as solvent polarity increases (see Table VII). The Stokes shift of indene 1a in cyclohexane is less than for the donor-only indene 1c. A similar situation is observed in the fluorescent solvatochromic dyes 19<sup>39</sup> and 20,<sup>40</sup> in which the Stokes losses are less than those of



the analogous protio compounds in hydrocarbon solvents. Thus, in the acceptor-substituted systems 1a, 19, and 20, the geometric relaxation pathway of the donor-only/protio system has been replaced by a charge-transfer/solvent relaxation deactivation mechanism.

The solvent-induced Stokes shifts in the indene 1a and stilbene 2a are consistently less than those of the corresponding metacompounds 1b and 2b, indicating less polar excited states. The exicted states of 1a and 2a are thus classified simply as intramolecular charge transfer (ICT), to differentiate them from the TICT states.41

Furthermore, the stilbene 2a suffers a greater Stokes loss than the indene 1a in any given solvent. The diminished Stokes shifts of the indene may arise from two factors. First, the bulky ring at C-3 and the methylene bridge may partially insulate the dipolar fragment of the indene from contact with the solvent. Such an insulating effect has been observed in the N,N-dialkylaniline series 21, 22, and 11.42 Although 21 and 22 each have a stronger donor



- (39) David, C.; Baeyens-Volant, D. Mol. Cryst. Liq. Cryst. 1980, 59, 181. (40) Johnson, I. D.; Thomas, E. W.; Cundall, R. B. J. Chem. Soc., Faraday Trans. 1985, 81, 1303.
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- (42) Kamlet, M. J.; Abboud, J. L.; Taft, R. W. J. Am. Chem. Soc. 1977, 99, 6027.

group than 11, their solvent sensitivity is less, suggesting a steric hindrance to solvation. However, the m-nitroindene 1b and *m*-nitrostilbene 2b show similar Stokes shifts in most solvents; apparently, in this case no insulating effect is operative for the indene. Since the insulating properties of both indenes 1a and 1b should be similar, this mechanism does not adequately explain the lesser solvent sensitivity of the *p*-nitroindene 1a compared to stilbene 2a

A second possibility is that the ring twist in the indenes (Figure 1) inhibits resonance and thereby reduces the extent of ICT. Attenuation of charge transfer by steric factors has been observed in nitroarenes<sup>42</sup> and anilines.<sup>43</sup> This mechanism is tentatively adopted to explain the lower fluorescence solvatochromism of indene 2a. If the fluorescence of the stilbene 2a originates from a planar ICT (PICT) state, the lower solvent-sensitivity fluorescence of **1a** can be described as arising from a quasi-planar ICT (QPICT) state.4b

Emission Intensities. The fluorescence quantum yields of the compounds described herein have not been determined. However, the quantum yield of the diphenol of 1a (of more biological relevance<sup>4a</sup>) has been determined to be 0.48 in EtOAc and 0.52 in THF.<sup>44</sup> On the basis of the similar fluorescence intensities and band shapes, the quantum yields of 1a are expected to be comparable. The fluorescence intensities of 1a-c and 2a-c can be compared to determine the relative importance of radiative and nonradiative processes (see Table VIII).

For the same state, the indene has greater intensity than the stilbene, due to its rigid structure, except for 1a versus 2a in CH<sub>3</sub>CN. In this more polar media, intersystem crossing (ISC) and radiationless decay may be more significant for the indene 1a than the stilbene 2a. Flash photolysis studies on 2a show an absorption at 700 nm assigned to the triplet.<sup>45</sup> In CH<sub>3</sub>CN, indene 1a emits at 660 nm, whereas stilbene 2a emits at 647 nm. Transition probabilities between states are proportional to the square of the inverse of the energy level difference between two states.<sup>46</sup> Assuming a similar triplet level for **1a** as **2a**, ISC is expected to be more important for 1a, because it emits at longer wavelengths. Also, in more polar media, radiationless decay is more important, due to dipole-induced dipole interactions.47 Simple 4,4'-substituted stilbenes are solvated by 17 solvent molecules.<sup>48</sup> The larger 2,3-diarylindene would have a more populous solvent shell, greater solute-solvent contacts, and enhanced radiationless decay.

The TICT-state compounds compared to their ICT counterparts (1b versus 1a; 2b versus 2a) give lower intensities. The forbidden TICT state typically has a lower quantum yield.<sup>27b</sup> Emission from the TICT state compounds 1b and 2b cannot be observed in solvents of higher polarity than CHCl<sub>3</sub> and acetone, respectively. Once again, the extreme long-wavelength emission of these compounds may be a factor in the ISC. The greater intensity of the indene TICT compared to that of the stilbene may be due to either

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<sup>(44)</sup> Anstead, G. M.; Katzenellenbogen, J. A. J. Med. Chem., 1988, 31, 1754.

<sup>(45)</sup> Bent, B. W.; Schulte-Frohlinde, D. J. Phys. Chem. 1974, 78, 446. (46) Seliskar, C. J.; Brand, L. J. Am. Chem. Soc. 1971, 93, 5414.
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the rigidity of the indene heretofore described or intensity borrowing (vibronic coupling) from the LE state.49 The degree of borrowing will depend on the separation between the LE and TICT states. The LE state of the indene (i.e., 1c) emits at longer wavelength than that of the stilbene (i.e., 2c), so the LE-TICT energy gap is less for the indenes and thus a higher quantum yield is expected for 1b.

Quantitative Aspects of Fluorescence Solvatochromism. This effect of solvent on the absorption spectrum is dependent on the energy levels of the quilibrium ground state and the Franck-Condon excited state, whereas that of the emission depends on the energy levels of the equilibrium excited state and the Franck-Condon ground state.<sup>30</sup> Compounds 1a,b and 2a,b show small solvent effects on the absorption spectra, but the emission properties are quite solvent sensitive. There have been numerous treatments of solvent dispersive and dipole interactions on the excited state.<sup>51</sup> For ellipsoidal molecules, eq 2 applies:

$$v_{\rm a} - v_{\rm f} = (2/hca^3)(\mu_{\rm e} - \mu_{\rm g})^2 f(D,n) + {\rm constant}$$
 (2)

where

$$F(D,n) = \frac{2n^2 + 1}{n^2 + 2} \frac{D - 1}{D + 2} - \frac{n^2 - 1}{n^2 + 2}$$
(3)

 $v_a$  and  $v_f$  refer to the absorption and emission frequencies, D and *n* are the solvent dielectric constant and refractive index,  $\mu_{g}$  and  $\mu_e$  are the ground- and excited-state dipole moments, and a is long axis radius of the ellipsoidal cavity (equivalent to the cavity within the solvent).52

For p-nitrostilbene 2a, the use of an ellipsoidal cavity is an excellent approximation, based on its pseudoelectron density function<sup>53</sup> (see Figure 6). Equations for fluorescence solvatochromism have been vehemently denounced for their use of the Onsager parameter a to evaluate the volume of the cavity occupied by an irregularly shaped molecule.<sup>54</sup> However, with molecular graphics, it is possible to calculate the molecular volume directly, by using the pseudoelectron density function, and make the following substitution: volume =  $a^{3.55}$  Volumes obtained in this way are still approximate in two respects. First, van der Waals radii have been criticized as being too voluminous.<sup>56</sup> Also, "harpooning"<sup>27b</sup> or electrostricture<sup>57</sup> may occur, in which the intramolecular electrostatic attractions in the excited state cause the molecule to contract.

A plot of  $v_a - v_f$  versus F(D,n) for a series of solvents yields a slope from which the value of  $(\mu_e - \mu_g)^2$  can be determined. For 2a, this plot was done with two solvent groups: (1) all the aprotic solvents examined; (2) a subgroup of well-behaved aprotic solvents, which do not have special dispersive forces.<sup>58</sup> The solvent properties are shown in Table IX.

The plots obtained by using eq 2 provide statistically valid correlations, but the points are quite scattered, typical of many applications of a continuum model of solvent-solute interactions<sup>60</sup> (see Table X). Using the volume of 207.6  $Å^3$  obtained from the

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Figure 6. Pseudoelectron density grid for 2a, contoured along the xyaxes: (a) plotted parallel to the best-plane normal; (b) plotted perpendicular to the best-plane normal; (c) view b rotated 90° (i.e., sighting down O-Ar bond). These grids were calculated by the volume command of the SYBYL molecular modeling system.



Figure 7. Pseudoelectron density grids for 1a,b and 2b contoured in the xy planes: (a) and (b) **1a** and **1b** plotted parallel to the best-plane normal, respectively; (c) 2b plotted as to sight down the O-Ar bond. Compounds 1b and 2b are in a TICT geometry; changes in the bond angles and bond lengths in the excited state are ignored.<sup>63</sup>

#### **TABLE IX:** Solvent Properties

	-			
solvent	n <sup>a,b</sup>	$D^{a,c}$	$F(D,n)^d$	well-behaved <sup>e</sup>
cyclohexane	1.423	2.02	-0.00126	Y
ČCl₄	1.457	2.24	0.0242	Ν
benzene	1.498	2.30	0.0147	Ν
ether	1.350	4.30	0.456	Y
dioxane	1.420	2.20	0.0412	Ν
THF	1.405	7.60	0.578	Y
EtOAc	1.370	6.00	0.490	Y
CHCl	1.443	4.80	0.373	Ν
CH <sub>2</sub> Cl <sub>2</sub>	1.421	10.4	0.630	Ν
acetone	1.356	20.7	0.793	Y
CH <sub>3</sub> CN	1.341	37.5	0.864	Y

<sup>b</sup>Refractive index. <sup>c</sup>Dielectric constant. <sup>a</sup>Reference 59. <sup>d</sup>Calculated by using eq 3. <sup>e</sup>Defined in reference 58.

TABLE X: Results of Plot of Stokes Shift versus F(D,n) for 2a

solvent	m <sup>a</sup>	rb	
all aprotic	3976	0.82	
well-behaved aprotic	4473	0.79	

<sup>a</sup>Slope. <sup>b</sup>Correlation coefficient.

TABLE XI: Dipole Moments of 1a,b and 2b<sup>a</sup>

compd	V, <sup>b</sup> Å <sup>3</sup>	$\mu_{g}$ , <sup>c</sup> D	m, <sup>d</sup> cm <sup>-1</sup>	re	$\Delta \mu, f$ D	$\mu_{e}$ , <sup>g</sup> D	
1a	310.6	8.36	4662.6	0.91	12.0	20.4	
1b	311.2	5.68	5809.5	0.93	13.4	19.1	
2b	219.2	5.10	5945.2	0.85	11.4	16.5	
$2a^h$	207.6	7.51	3975.8 <sup>i</sup>	0.82	9.05	16.6 <sup>j</sup>	

<sup>a</sup> From use of eq 2. <sup>b</sup> Volumes based on pseudoelectron density functions. Ground-state dipole moments calculated by the MNDO method.<sup>64</sup> <sup>d</sup> Slope of the plot for well-behaved solvents. Correlation coefficient. <sup>f</sup>Defined as  $\mu_e - \mu_g$ . <sup>g</sup>Excited-state dipole moments. <sup>h</sup>Included for comparison purposes. <sup>f</sup>Slope for the plot of aprotic solvents. <sup>1</sup>Calculated by using the MNDO ground-state dipole moment.

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<sup>(50)</sup> Mataya, N.; Kaifu, Y.; Koizumi, M. Bull. Chem. Soc. Jpn. 1955, 28, 690.

<sup>(51)</sup> Reference 15 and references cited therein.

<sup>(52) (</sup>a) Kawski, A. Acta Phys. Polon. 1966, 29, 507. (b) Chamma, A.; Viallet, P. C. R. Acad. Sci. Ser. C 1970, 270, 1901. (c) Walker, M. S.; Miller, R. L.; Kuder, J. E. J. Phys. Chem. 1972, 76, 2240.

<sup>(53)</sup> The pseudoelectron density map was generated by using Gaussian functions surface contoured at a level representative of the van der Waals radii; see: Marshall, G. R.; Barry, C. D. Abstracts of the Meeting of the American Crystallographic Association; Honolulu, 1979

<sup>(55)</sup> This is an adaptation of the equivalent shell model; see: Ledger, M.



Figure 8. LUMO coefficients of nitrobenzene, based on AM1 calculations.67

pseudoelectron density map, an experimental dipole moment of 6.31 D,61 and the slope obtained for aprotic solvents, eq 2 provides  $\Delta \mu = 9.05 \text{ D}$  and  $\mu_e = 15.4 \text{ D}$  for 2a.<sup>62</sup> These values for  $\Delta \mu$  and  $\mu_e$  are less than those calculated by others for many solvatochromic dyes. However, many authors simplistically treat the molecules as spheres, using the Lippert equation,<sup>63</sup> which overestimates the value of  $\Delta \mu$ . If **2a** is treated as a sphere, the Lippert equation gives  $\Delta \mu = 15.0$  D. Also, many authors use erroneous approximations for the Onsager radii and also include protic solvents in the plot, which typically produce larger Stokes shifts than expected, on the basis of their bulk dielectric properties.<sup>15</sup> The Lippert equation is reported to give errors of 25-50%. 46,63c

For **1a**,**b** and **2b** the situation is more complicated. Equation 2 is valid only if the dipole moments of the ground and excited states are collinear. This is a good assumption for para-substituted aromatics,<sup>63</sup> such as 2a, but it is not valid for meta-substituted TICT-emitting compounds. Furthermore, 1a,b and 2b defy simple topographical description and thus cannot be treated accurately by the usual solvatochromism equations. *m*-Nitrostilbene 2b in its assumed TICT-state geometry has a cruciform profile, whereas indenes 2a,b are roughly T-shaped (see Figure 7). The protruding 4-methoxyphenyl group at C-3 of the indenes may also contribute charge to the ground and excited states, so these molecules do not behave as mere dipoles. Despite these sources of inaccuracy, eq 2 was used to calculate the  $\mu_e$  of **1a**,**b** and **2b** (see Table XI). The  $\Delta \mu$  values of Table XI appear to be erroneous (except for those of 2a) on intuitive grounds. For a given molecule in a given solvent,  $\Delta \mu$  is proportional to the Stokes shift.<sup>15</sup> In any of the solvents examined, the Stokes shift of  $1b = 2b \gg 2a > 1a$ , an order that differs from the calculated values of  $\Delta \mu$ : 1b > 1a > 2b > 2a. This illustrates the pitfalls of using the solvatochromism equations, unless they can be applied to nearly ideal systems, such as 2a. Molecules such as 1a,b and 2b are better treated by the more rigorous microstructural solvent-interaction (MSI) approach, which considers actual molecular shapes and charge distributions.<sup>54</sup> Application of this model would require additional computational effort.

Regiochemical Effects on Excited-State Properties (p-NO<sub>2</sub> versus m-NO<sub>2</sub>; ICT versus PICT). The occurrence of an ICT emission from the p-NO<sub>2</sub> compounds 1a and 2a and a TICT emission from m-NO<sub>2</sub> compounds 1b and 2b requires discussion. A few cases of substitutional isomer effects on the formation of the TICT state have been reported. p-Aminobenzoic acid emits from a TICT state, but the meta isomer does not.65 7-Aminocoumarin 23 displays ICT fluorescence, whereas 6-aminocoumarin 24 shows TICT fluorescence.<sup>66</sup> In both cases, the occurrence of the TICT state has been justified on the basis of the Coulombic



term C in eq 1. The Coulombic term is proportional to the square of the HOMO coefficients of the donor and the LUMO coefficients of the acceptor. For a given donor/acceptor pair, the IP(D), EA(A), and  $\Delta E_{solv}$  terms of eq 1 should be the same; C is the factor that should determine which of a series of different isomers possesses the lowest lying TICT state.<sup>27b</sup> However, in **1a,b** and 2a,b this situation does not hold. The square of the LUMO coefficients of nitrobenzene is greater at the para and ortho positions and small at the meta position (Figure 8).

Perhaps the relationship breaks down in the elongated stilbene systems because in smaller molecules the normalization condition increases the size of the MO coefficients.68 Also, LUMO coefficients change according to the twist angle of a nitro group.<sup>69</sup> We have assumed this angle to be  $\approx 0^{\circ}$ , a reasonable assumption for many meta- and para-substituted nitroarenes, but not all.<sup>70,71</sup> More detailed structural studies on these compounds may be necessary to fully understand their emissive behavior.

#### Conclusions

Potential Utility. The indenes 1a-c may be useful as environmentally sensitive fluorescent probes in biological or polymer systems.<sup>1,72</sup> All three compounds show absorbance and emission outside the range of proteins and nucleic acids.<sup>73</sup> The methyl ethers permit ready cleavage and subsequent chemical modification, providing polar, hydrophobic, surfactant,<sup>74</sup> or covalently labeling<sup>75</sup> analogues. Unlike amine donors, the methyl ether is immune to quenching in acidic solution.<sup>76</sup> The indenes may also be fluorescence indicators of redox processes,<sup>77</sup> because the oxidation products, the indenones, are not appreciably fluorescent.<sup>4d</sup>

The Stokes shift of the donor-only indene 1c is the result of a geometric relaxation process, with little solvent polarity influence. Thus, this compound may be useful as a probe of viscosity, with little interference from the polarity of the medium.

The advantages of using molecules that fluorescence via TICT states as probes of polymer systems has been recently espoused by Hayashi et al.<sup>78</sup> The readily discernible dual fluorescence of 1b provides an additional emission parameter for scrutiny. The partitioning of the fluorescence between the LE and TICT states is sensitive to solvent polarity, mobility, viscosity, and specific quenchers.

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<sup>(61)</sup> The experimental dipole moment used for 2a is the average of three determinations from the literature; see: (a) Everard, K. B.; Kumar, L.; Sutton, L. E. J. Chem. Soc. 1951, 2807. (b) Moll, F.; Lippert, E. Z. Elektrochem. 1954, 58, 853. (c) Weizmann, A. Trans. Faraday Soc. 1940, 36, 329.

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<sup>(71)</sup> It is also possible that the nitro group may alter the torsional angle of the pendant aryl rings of the indene with respect to the double bond, as observed in other systems (Rettig, W.; Rotkiewicz, K.; Rubaszewska, W. Spectrochim. Acta, Part A 1984, 40, 241); this may also affect the MO properties.

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Indene 1a meets several criteria of a fluorophore intended for use in biological studies:<sup>77</sup> (1) large Stokes shift, obviating interference from the solvent Raman band; (2) high sensitivity to the environment; (3) long emission wavelength (i.e., >500 nm), for detection in the presence of cellular fluorophores; (4) high intensity, allowing subnanomolar detectability in solution. The Stokes shifts of 1a,b exceed those of Prodan<sup>3</sup> and Nile red,<sup>79</sup> two widely used polarity probes.

The indenes 1a-c may be of particular interest as probes of proteins that demonstrate selective binding to triarylethylenes, such as the estrogen receptor,<sup>80</sup> prostaglandin synthetase,<sup>81</sup> glutamate dehydrogenase,<sup>82</sup> estrogen binding factor,<sup>83</sup> the Z-protein,<sup>84</sup> antiestrogen binding protein,<sup>85</sup> protein kinase C,<sup>86</sup> and calmodulin.<sup>87</sup> We are currently pursuing the simultaneous optimization of estrogen receptor binding affinity and fluorescence properties in the 2,3-diarylindene system.

#### Experimental Section

General. Melting points (uncorrected) were determined on a Thomas-Hoover apparatus. Analytical thin-layer chromatography (TLC) was performed on Merck silica gel F-254 glass-backed plates. Flash chromatography was done as previously described,<sup>88</sup> by using Woelm  $32-63-\mu m$  silica gel.

Proton nuclear magnetic resonance (<sup>1</sup>H NMR) spectra were obtained on a Varian XL-200 (200 MHz) or a General Electric QE-300 (300 MHz) spectrometer; chemical shifts are reported downfield from a tetramethylsilane internal standard ( $\delta$  scale). Infrared (IR) spectra were obtained on a Nicolet 700 spectrometer in the indicated phase: prominent and diagnostic peaks are reported. Ultraviolet (UV) spectra were determined with a Hewlett-Packard 8451A spectrophotometer. Low-resolution mass spectra (MS) were done in the electron impact made on the Varian CH-5 spectrometer. The reported data are from an electron energy of 70 eV and follows the form of m/z (intensity relative to base peak = 100). High-resolution mass spectra (HRMS) were obtained in the electron impact mode on a Varian MAT-371 spectrometer. The corrected fluorescence emission spectra were acquired on a Spex Fluorolog III. Elemental analyses were performed by the Microanalytical Service Laboratory of the University of Illinois.

Unless otherwise noted, a standard procedure for product isolation was used; this involved quenching by addition of water or an aqueous solution, exhaustive extraction with an organic solvent, washing the extracts, drying with  $MgSO_4$ , and solvent evaporation under reduced pressure. The quenching media, extraction solvents, and aqueous washes used are noted parenthetically after the phrase "product isolation".

Calculations and Molecular Graphics. The SYBYL molecular modeling system (version 3.4, Tripos Associates, St. Louis, MO) was used for molecular building, graphics, force field, pseudoelectron density mapping, and volume calculations and as an interface for MO (MNDO, AM1) calculations. Stilbenes **2a,b** were assembled by joining fragments retrieved from a library of crystallographically determined structures. The resulting structures were minimized by using molecular mechanics (MAXIMIN). The structures of the indenes **1a,b** were based on the X-ray crystal structure of 2,3-bis(4-methoxyphenyl)-6-methoxyindene,<sup>4d</sup> with

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the appropriate group deletions and attachments and no minimization. The structures obtained in each case were than subjected to MNDO calculations. The geometry of nitrobenzene was optimized with AM1, and the LUMO was calculated based on this geometry.

General Method for Preparation of 4-Anisyl Benzyl Ketones. The substituted phenylacetic acid (16.5 mmol) and anisole (21.5 mmol) were added to polyphosphoric acid (PPA;  $10 \times$  the weight of the acid). The mixture was stirred at 50–70 °C and monitored by TLC. The reaction was complete in 2–6 h. Product isolation (ice water, EtOAc, saturated NaHCO<sub>3</sub>) was followed by purification as described.

1-(4-Methoxyphenyl)-2-(4-nitrophenyl)ethanone (**3a**). The residual solid was recrystallized from methanol at -78 °C to give a slightly off-white solid (2.9 g, 65%): mp 112-113 °C; IR (CHCl<sub>3</sub>) 1680, 1600, 1520, 1350 cm<sup>-1</sup>; <sup>1</sup>H NMR (CDCl<sub>3</sub>) δ 8.19 (d, 2 H, J = 9 Hz, ArH ortho to  $-NO_2$ ), 7.99 (d, 2 H, J = 9 Hz, ArH ortho to  $-NO_2$ ), 7.99 (d, 2 H, J = 9 Hz, ArH ortho to  $-OCH_3$ ), 4.36 (s, 2 H,  $-CH_2$ -), 3.88 (s, 3 H,  $-OCH_3$ ); MS 271 (1, M<sup>+</sup>), 135 (100), 86 (40). Anal. Calcd for C<sub>15</sub>H<sub>13</sub>NO<sub>4</sub>: C, 66.41; H, 4.83; N, 5.16. Found: C, 66.07; H, 4.78; N, 5.04.

*l*-(4-Methoxyphenyl)-2-(3-nitrophenyl)ethanone (**3b**). Purification was achieved by flash chromatography (9:1 hexane-EtOAc). A white solid was obtained (0.85 g, 56%): mp 58-60 °C; IR (CHCl<sub>3</sub>) 3010, 1680, 1600, 1530, 1355, 1270 cm<sup>-1</sup>; <sup>1</sup>H NMR (CDCl<sub>3</sub>)  $\delta$  8.05-8.02 (m, 2 H, ArH ortho to -NO<sub>2</sub>), 7.92 (d, 2 H, J = 9 Hz, ArH ortho to -CO-), 7.50-7.37 (m, 2 H ortho to -OCH<sub>3</sub>), 4.28 (s, 2 H, -CH<sub>2</sub>-), 3.80 (s, 3 H, -OCH<sub>3</sub>); MS 271 (0.5, M<sup>+</sup>), 135 (100). Anal. Calcd for C<sub>15</sub>H<sub>3</sub>NO<sub>4</sub>: C, 66.41; H, 4.83; N, 5.16. Found: C, 66.54; H, 4.66; N, 5.07.

1-(4-Methoxyphenyl)-2-(4-nitrophenyl)-3-(3-methoxyphenyl)-1-propanone (4a). Diisopropylamine (410 mg, 4.07 mmol) was added to THF (5 mL) and cooled to 0 °C. A solution of n-butyllithium in hexane (2.27 mL, 1.55 M, 3.9 mmol) was added by syringe. Ketone 3a (1.0 g, 3.7 mmol), dissolved in THF (15 mL), was added dropwise over 1 h. After an additional 0.5 h, 3-methoxybenzyl chloride (870 mg, 5.55 mmol) and lithium iodide (25 mg, 0.15 mmol), dissolved in 5 mL of THF, were added. The reaction was stirred at 25 °C for 36 h and at 50 °C for 6 h. Product isolation (5% HCl, EtOAc, brine), followed by flash chromatography (3:1 hexane-EtOAc), gave a yellow oil (1.00 g, 70%): IR (CHCl<sub>3</sub>) 3005, 1670, 1595, 1520, 1340, 1215 cm<sup>-1</sup>; <sup>1</sup>H NMR (CDCl<sub>3</sub>)  $\delta$  8.10 (d, 2 H, J = 9 Hz, ArH ortho to -NO<sub>2</sub>), 7.88 (d, 2 H, J = 9 Hz, ArH ortho to -CO-), 7.40 (d, 2 H, J = 9 Hz, ArH meta to  $-NO_2$ ), 6,86 (d, 2 H, J = 9 Hz, ArH meta to -CO), 6.75–6.55 (m, 4 H, ArH), 4.90 (t, 1 H, J = 7 Hz, -CH-), 3.81 (s, 3 H, -COArOCH<sub>3</sub>), 3.71 (s, 3 H, ArOCH<sub>3</sub>), 3.54  $(dd, 1 H, J = 14, 8 Hz, -CH_2-), 3.50 (dd, 1 H, J = 14, 8 Hz,$ -CH<sub>2</sub>-); MS 391 (9, M<sup>+</sup>), 360 (3), 241 (15), 135 (100), 121 (65). HRMS calcd/found (C<sub>23</sub>H<sub>21</sub>NO<sub>5</sub>) 391.1420/391.1420.

*1-(4-Methoxyphenyl)-2-(3-nitrophenyl)-3-(3-methoxyphenyl)-1-propanone* (**4b**). This compound was prepared from ketone **3b** in a manner similar to **4a**. Flash chromatography afforded a yellow oil (0.68 g, 61%): IR (CHCl<sub>3</sub>) 1675, 1600, 1460, 1360 cm<sup>-1</sup>; <sup>1</sup>H NMR (CDCl<sub>3</sub>)  $\delta$  8.13–8.08 (m, 2 H, ArH ortho to -NO<sub>2</sub>), 7.90 (d, 2 H, J = 9 Hz, ArH ortho to -CO-), 7.63–7.58 (m, 1 H, ArH para to -NO<sub>2</sub>), 7.43 (t, 1 H, J = 8 Hz, ArH meta to -NO<sub>2</sub>), 7.15 (t, 1 H, J = 7.5 Hz, ArH meta to -CH<sub>2</sub>-), 6.86 (d, 2 H, J = 9 Hz, ArH meta to -CO-), 6.72–6.58 (m, 3 H, ArH ortho and para to -CH<sub>2</sub>-), 4.92 (t, 1 H, J = 7 Hz, -CH-), 3.82 (s, 3 H, -COArOCH<sub>3</sub>), 3.70 (s, 3 H, -OCH<sub>3</sub>), 3.54 (dd, 1 H, J = 14, 7 Hz, -CH<sub>2</sub>-), 3.07 (dd, 1 H, J = 14, 7 Hz, -CH<sub>2</sub>-); MS 319 (3, M<sup>+</sup>), 135 (100). Anal. Calcd for C<sub>23</sub>H<sub>21</sub>NO<sub>5</sub>: C, 70.58; H, 5.41; N, 3.58. Found: C, 70.46; H, 5.51; N, 3.57.

General Procedure for Polyphosphoric Acid Cyclizations. The triaryl ketones 4a,b were mixed with  $10 \times$  their weight of polyphosphoric acid (PPA). The mixture was stirred mechanically under nitrogen at 45 °C, and the reaction was monitored closely by TLC. Product isolation (ice water, EtOAc, saturated NaH-CO<sub>3</sub>) was followed by purification of the residual solid as described.

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2-(4-Nitrophenyl)-3-(4-methoxyphenyl)-6-methoxyindene (1a). The crude solid was triturated with methanol to give an orange solid (1.0 g, 50%). The analytical sample was obtained by preparative TLC (4:1 hexane-EtOAc), followed by recrystallization from methanol: mp 163-164 °C; IR (CDCl<sub>3</sub>) 1590, 1510, 1340, 1250 cm<sup>-1</sup>; <sup>1</sup>H NMR (CDCl<sub>3</sub>)  $\delta$  8.08 (d, 2 H, J = 9 Hz, ArH ortho to -NO<sub>2</sub>), 7.53 (d, 2 H, J = 9 Hz, ArH meta to  $NO_2$ ), 7.30 (d, 2 H, J = 9 Hz, ArH meta to  $-OCH_3$  on 4-MeOAr-), 7.24-7.01 (m, 4 H, ArH), 6.91 (dd, 1 H, J = 8, 2 Hz, ArH ortho to  $-OCH_3$ , para to  $-CH_2$ -), 3.99 (s, 2 H,  $-CH_2$ -), 3.88 (s, 3 H,  $-OCH_3$ ), 3.85 (s, 3 H,  $-OCH_3$ ); MS 373 (100, M<sup>+</sup>), 358 (11), 342 (4), 330 (2). Anal. Calcd for C<sub>23</sub>H<sub>19</sub>NO<sub>4</sub>: C, 73.98; H, 5.13; N, 3.75. Found: C, 73.99; H, 5.38; N, 3.58.

2-(3-Nitrophenyl)-3-(4-methoxyphenyl)-6-methoxyindene (1b). The crude solid was recrystallized from methanol at -30 °C to provide yellow needles (0.39 g, 70%). The analytical sample was obtained by a second recrystallization from acetone-pentane at -30 °C: mp 152–153 °C; IR (CHCl<sub>3</sub>) 3010, 1590, 1510, 1340, 860 cm<sup>-1</sup>; <sup>1</sup>H NMR (CDCl<sub>3</sub>)  $\delta$  8.15–7.93 (m, 2 H, HArNO<sub>2</sub>), 7.52–7.11 (m, 6 H, ArH), 6.98 (d, 2 H, Ar H ortho to  $-OCH_3$  on 4-MeOAr-), 6.88–6.83 (m, 1 H, ArH), 3.90 (s, 2 H,  $-CH_2$ -), 3.87 (br s, 6 H, both  $-OCH_3$ ); MS 373 (100, M<sup>+</sup>), 358 (10), 343 (6), 326 (2). Anal. Calcd for C<sub>23</sub>H<sub>19</sub>NO<sub>4</sub>: C, 73.98; H, 5.13; N, 3.75. Found: C, 73.67; H, 5.34; N, 3.62.

(*E*)-4-Methoxy-4'-nitrostilbene (**2a**). Ketone **3a** (300 mg, 1.11 mmol) was suspended in methanol (20 mL), and sodium borohydride (100 mg, 2.6 mmol) was added. After 1 h, the solvent was evaporated, and the resultant white solid was suspended in 6 M HCl and heated at 70 °C for 3 h. Product isolation (EtOAc, brine) and recrystallization from ethanol at -30 °C provided canary yellow flakes (203 mg, 72%): mp 125-127 °C (lit.<sup>6</sup> mp 132-133 °C); IR (CHCl<sub>3</sub>) 1590, 1510, 1340, 1250 cm<sup>-1</sup>; <sup>1</sup>H NMR (CDCl<sub>3</sub>)  $\delta$  8.20 (d, 2 H, J = 9 Hz, ArH ortho to -NO<sub>2</sub>), 7.60 (d, 2 H, J = 9 Hz, ArH meta to -NO<sub>2</sub>), 7.50 (d, 2 H, J = 9 Hz, ArH meta to -NO<sub>2</sub>), 7.04 (s, 1 H, -CH= para to -NO<sub>2</sub>), 6.93 (d, 2 H, J = . Hz, ArH ortho to  $-OCH_3$ ), 3.85 (s, 3 H,  $-OCH_3$ ); MS 255 (100, M<sup>+</sup>), 240 (2), 255 (50), 209 (7), 194 (4), 166 (8). Anal. Calcd for  $C_{15}H_{13}NO_3$ : C, 70.58; H, 5.13; N, 5.49. Found: C, 70.41; H, 5.20; N, 5.43.

(E)-4-Methoxy-3'-nitrostilbene (2b). 3-Nitrophenylacetic acid (1.0 g, 5.5 mmol), 4-anisaldehyde (750 mg, 5.5 mmol), and piperidine (1.5 g, 18 mmol) were combined and heated at 150 °C for 12 h. Product isolation (6 M HCl, CH2Cl2, saturated NaH- $CO_3$ ) and purification by flash chromatography (two runs; 9:1 hexane-EtOAc), followed by recrystallization (Et<sub>2</sub>O, -30 °C), gave a yellow solid (45 mg, 3%): mp 87.5-89 °C; IR (CHCl<sub>3</sub>) 1600, 1530, 1510, 1350, 1250 cm<sup>-1</sup>; <sup>1</sup>H NMR (CDCl<sub>3</sub>) δ 8.33 (t, 1 H, J = 2 Hz, ArH ortho to -NO<sub>2</sub>, ortho to -CH-), 8.06 (dd, 1 H, J = 8 2 Hz, ArH ortho to  $-NO_2$ , para to -CH =), 7.76 (d, 1 H, J = 8 Hz, ArH para to -NO<sub>2</sub>), 7.52 (d? (obscured by adjacent signal), ArH meta to  $-NO_2$ ), 7.47 (d, J = 8 Hz, ArH meta to  $-OCH_3$ , 7.19 (d, 1 H, J = 16 Hz, -CH=) meta to  $-NO_2$ , 6.99 (d, 1 H, J = 16 Hz, -CH = para to  $-OCH_3$ ), 3.92 (s, 3 H, -CH<sub>3</sub>); MS 255 (100, M<sup>+</sup>), 240 (3), 209 (3), 194 (4), 178 (5). Anal. Calcd for C<sub>15</sub>H<sub>13</sub>NO<sub>3</sub>: C, 70.58; H, 5.13; N, 5.49. Found: C, 70.34; H, 4.98; N, 5.37.

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