JOC Article

Photochemical Elimination of Leaving Groups from Zwitterionic Intermediates Generated via Electrocyclic Ring Closure of α,β-Unsaturated Anilides

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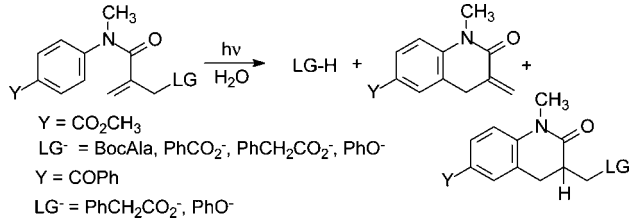

Methacrylanilides, $ArN(CH_3)COC(CH_2LG)=CH_2$, with allylic leaving groups (LG^- = BocAla, $PhCO_2^-$, $PhCH_2CO_2^-$, PhO^-) undergo photochemical electrocyclic ring closure to produce a zwitterionic intermediate. Further reaction of the intermediate results in expulsion of the leaving group to give an α-methylene lactam as the major product. In addition, a lactam product that retains the leaving group is formed via a 1,5-H shift in the intermediate. Elimination of the leaving group is generally preferred, even for LG^- = PhO^-, although in benzene as the solvent the lactam retaining the phenolate group becomes the sole photoproduct. The electrocyclic ring closure occurs in the singlet excited-state for the *para*-COPh-substituted anilide derivative and is not quenched by 0.15 M piperylene or 0.01 M sodium 2-naphthalenesulfonate (2-NPS) as triplet quenchers. Comparable concentrations of 2-NPS strongly quench the transient absorption of the triplet excited state observed at 450−700 nm according to laser flash photolysis experiments. In aqueous media, quantum yields for total products are insensitive to leaving group ability, and Φ_{tot}(*para*-CO_2CH_3) = 0.04−0.06 at 310 nm and Φ_{tot}(*para*-COPh) = 0.08−0.1 at 365 nm, for which Φ_{isc} = 0.15.

Introduction

Nonoxidative photocyclizations of α,β-unsaturated anilides such as **1a** to give lactams have been known for over 40 years.[1,2] The photochemical reaction likely proceeds via an electrocyclic ring closure to give an intermediate that has zwitterionic character (Scheme 1).[3,4] The zwitterionic intermediate is converted to a lactam photoproduct via either intramolecular 1,5-H rearrangement or a series of proton transfers, depending on the solvent and the substituents attached to the amide nitrogen.[3,5,6]

The putative zwitterionic intermediates involved in anilide photocyclizations are of interest because recent studies of α-keto amide photochemistry have shown[7,8] that analogous zwitterionic intermediates are capable of eliminating leaving group anions ranging in basicity from carboxylates to phenolates. Zwitterionic intermediates have also been postulated to account for leaving group expulsions observed upon photochemical electrocyclization of enamides and benzanilides.[9−11] We have focused upon exploiting zwitterionic intermediates, generated via such excited-

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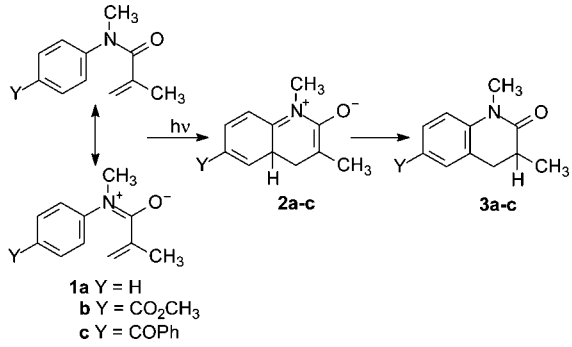
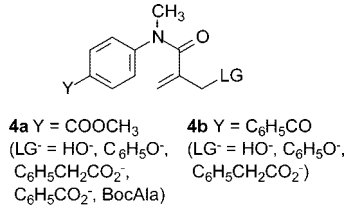
SCHEME 1



state electrocyclic ring closure reactions, for the ultimate purpose of releasing leaving groups that are biologically active. Photochemical generation of zwitterionic intermediates that release bioeffector leaving groups would constitute a new approach for the design of caged biological substrates that are generally used to trigger biological processes under physiological conditions.[12] The α,β-unsaturated anilide photoremovable protecting group can be synthesized through acylation of aniline derivatives. Since the aniline group is a common structural motif in long-wavelength absorbing organic dyes, α,β-unsaturated anilides would offer the prospect for achieving the release of biologically important leaving groups at biologically benign wavelengths.

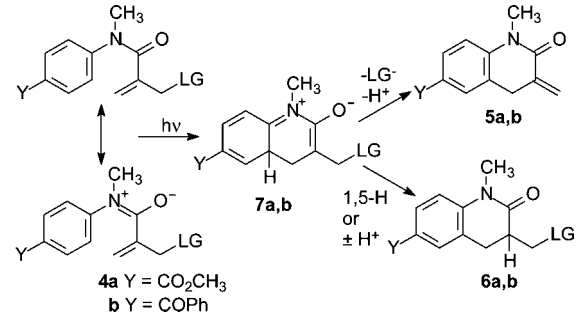


In this paper, we report in full[13] on our mechanistic investigation of the photochemical elimination reactions of anilides **4a**,**b** bearing various leaving groups (LG^-) at the allylic position of the α-methylacrylamide group. Under aqueous conditions, expulsion of the leaving groups generally occurs to give α-methylene lactams **5a**,**b** as the cleavage coproducts (Scheme 2).

Although lactams **6a**,**b**, which retain the leaving groups, are usually found to be minor products, **6a**,**b** can become the principal photoproducts if the leaving group is poor ($LG^- = HO^-$) or if the solvent is changed from an aqueous buffer to a nonpolar solvent such as benzene, as in the case of a relatively basic leaving group such as phenoxide ($LG^- = PhO^-$). These results are consistent with the intermediacy of a ground-state zwitterionic species, **7a**,**b**, which partitions between **5a**,**b** and **6a**,**b** in the photochemistry of **4a**,**b** (Scheme 2).

The zwitterionic intermediates **7a**,**b** are thought to be formed by an electrocyclic ring closure step that occurs in the excited state. We show that the presence of the allylic leaving groups has little effect on the efficiencies for this ring closure step, according to quantum yields for products of direct photolysis

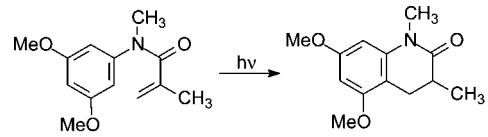
SCHEME 2



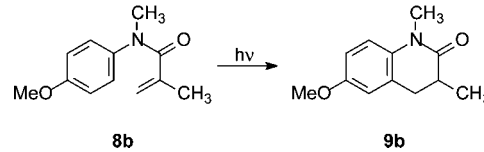
of **4a**,**b**. The total quantum yields for **5a**,**b** + **6a**,**b** in Scheme 2 are insensitive to leaving group basicity, and they are similar to those found for formation of lactams **3b**,**c** from **1b**,**c**, which have no leaving groups. These data suggest that expulsion of the leaving groups does not occur directly in an excited state of **4a**,**b**.

At the outset of our study, the para substituents, $Y = CO_2CH_3$ and Y = PhCO in **4a**,**b**, were thought to be necessary because recent reports[2] showed that such para-substituted derivatives **1b**,**c** were capable of overcoming a previously reported[4] strongly adverse polar solvent effect on the photoreactivity of **1a**, which was thought to be due to efficient intersystem crossing in polar solvents to give an unproductive triplet excited state. We therefore investigated the multiplicity of the photochemistry of the benzoyl derivatives **1c** and **4b**. Our results establish that the reactive excited-state for both compounds is the singlet excited-state and that the efficiency of intersystem crossing is insensitive to solvent polarity.

Substituent effects on efficiencies for excited-state electrocyclic ring closure were explored by comparing the quantum yields for **1b** with anilides **8a**,**b**, which should be subject to a "meta−ortho" effect in the excited-state (eqs 1 and 2).[14,15]



(1)



(2)

Accordingly, the electron-donating substituents in the aromatic ring of **8a** or **8b** should transmit electron density to the meta and ortho positions in the singlet excited state, which would potentially promote electrocyclization with the electron-deficient methacrylamide double bond. However, quantum yields were found to be essentially the same for **8a** and **1b** or lowered with **8b**.

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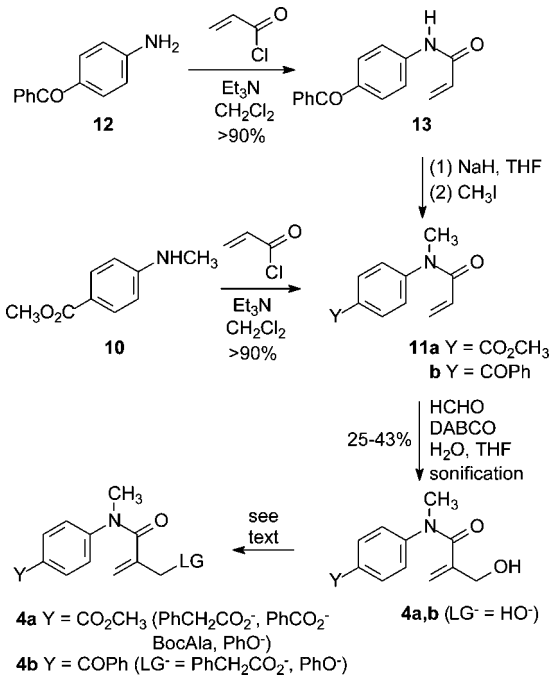
SCHEME 3



Results

Photochemical Reactants. The synthesis of anilides **4a** involved the acylation of *N*-methylaniline **10** (Scheme 3) to give the acrylamide **11a**. Baylis−Hillman reaction[16] of the acrylamide **11a** furnished the allylic alcohol **4a** ($LG^- = HO^-$) after 48 h of sonification at 50−60 °C. The carboxylate leaving groups were introduced via acylation of the allylic hydroxyl group of **4a** with $PhCH_2COCl$ or PhCOCl in CH_2Cl_2 with $(C_2H_5)_3N$ as base or by coupling of BocAla using DCC and DMAP in CH_2Cl_2. The allylic alcohol was converted into the phenolate derivative by Mitsunobu reaction (PhOH, DEAD, Ph_3P, DMF, or THF).[17]

The synthesis of anilides **4b** followed a similar sequence of reactions as for **4a** (Scheme 3). 4-Aminobenzophenone **12** served as the starting material, in which case the *tert*-amide **11b** was obtained by methylation of amide **13**.

Anilides **1b**,**c**, which have no leaving groups, were synthesized for comparisons of their excited-state properties and photochemistry to those of **4a**,**b**. These amides were readily obtained by acylation of arylamines **10** and **12** using α-methylacryloyl chloride in CH_2Cl_2 containing $(C_2H_5)_3N$, followed by a further alkylation step (NaH, DMF, then CH_3I) for **1c**. The 4-methoxy and 3,5-dimethoxyanilides **8a**,**b** were synthesized from 4-methoxyaniline and 3,5-dimethoxyaniline in >80% overall yields following the same acylation/methylation sequence as used for the synthesis of **4b** (Experimental Section).

^{1}H NMR analyses showed that anilides **4a**,**b**, bearing various leaving groups, were stable for at least one week in 50% D_2O in CD_3CN containing 100 mM phosphate buffer at pD 7. In both aqueous CH_3CN and neat CH_3CN, anilide **4a** ($LG^- = PhCH_2CO_2^-$) showed a UV absorption maximum below 300 nm, which tailed out into the 300−350 nm region (Figure 1). For the benzoyl derivative **4b** ($LG^- = PhCH_2CO_2^-$), the UV absorption extended to longer wavelengths, and photolyses of these compounds could routinely be conducted at 365 nm (ε 127 for $LG^- = PhCH_2CO_2^-$).

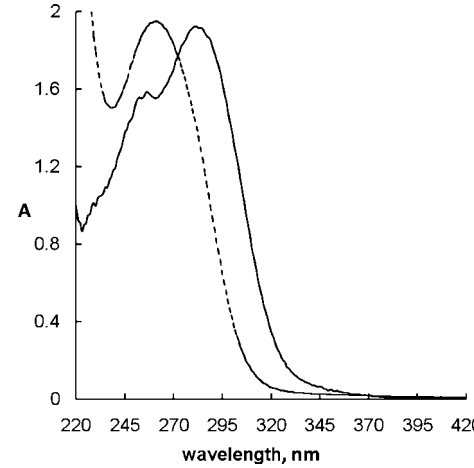
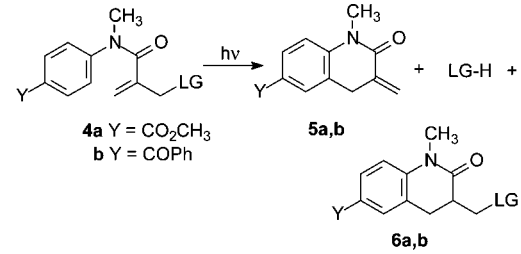


FIGURE 1. Absorption spectra of 0.156 mM **4a** ($LG^- = PhCH_2CO_2^-$, ----) and 0.169 mM **4b** ($LG^- = PhCH_2CO_2^-$, −) in CH_3CN.

Preparative Direct Photolyses. Preparative direct photolyses of 0.006 M **4a** ($LG^- = PhCH_2CO_2^-$) with unfiltered light from a medium pressure mercury lamp in N_2 saturated 50% aq CH_3CN containing 100 mM phosphate buffer at pH 7 for 7 h resulted in the release of phenyl acetic acid to give **5a** as the cleavage coproduct. A minor accompanying product was lactam **6a** ($LG^- = PhCH_2CO_2^-$) according to ^{1}H NMR spectroscopy, which showed ca. 2:1 ratio of **5a**/**6a** (eq 1). The products were separated chromatographically to obtain pure **5a**.



(3)

The minor lactam **6a** ($LG^- = PhCH_2CO_2^-$) was difficult to separate and therefore was independently synthesized (Scheme 4) via acylation of alcohol **6a** ($LG^- = HO^-$), which was obtained as the sole product from a preparative scale photolysis of 0.008 M **4a** ($LG^- = HO^-$) in N_2 saturated benzene containing a small amount of *p*-methoxyphenol as a radical inhibitor (Experimental Section).

Direct photolyses of solutions of 0.06 M **4a** ($LG^- = PhCO_2^-$, BocAla) in 50% D_2O in CD_3CN containing phosphate buffer at pD 7 in NMR tubes using a Pyrex filter gave α-methylene lactam **5a** upon loss of the leaving group. Lactams **6a** (LG^- = BocAla, $PhCO_2^-$) were observed as minor products. Samples of both lactams **6a** ($LG^- = PhCO_2^-$, BocAla) were obtained by independent synthesis through acylation of **6a** ($LG^- = HO^-$) (Scheme 4). Similarly, photolysis of the phenolate derivative **4a** ($LG^- = PhO^-$) in 50% D_2O in CD_3CN containing buffer produced α-methylene lactam **5a** upon loss of the leaving group, along with lactam **6a** ($LG^- = PhO^-$) as a minor product. When the solvent was changed to benzene, photolysis gave **6a** (LG^- = PhO^-) as the sole product, which was also obtained on a preparative scale by photolysis of 10^{-3} M **4a** ($LG^- = PhO^-$).

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SCHEME 4

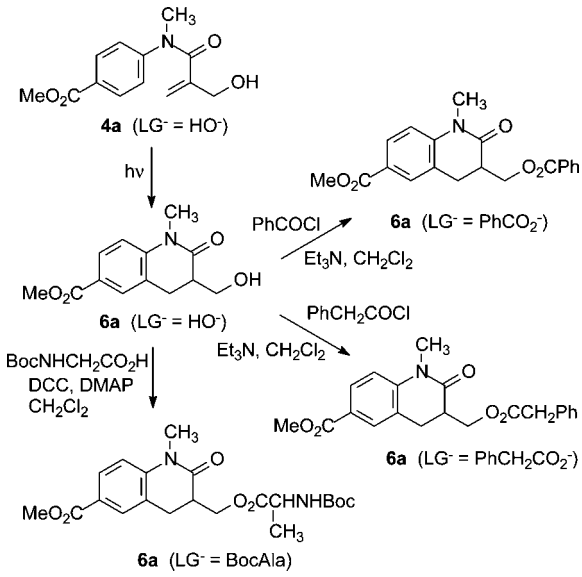


TABLE 1. Chemical Yields[a] for Photolyses of 4a (LG^- = BocAla, $PhCO_2$, $PhCH_2CO_2^-$, HO^-, PhO^-) in Various Solvents

reactant, LG^-	solvent	LG-H, %	**5a**, %	**6a**, %	unreacted **4a**, %
BocAla	buffer[b]	nd[d]	18[c]	7.3[c]	70
$PhCO_2^-$	buffer[b]	nd[d]	19[c]	7.4[c]	71
$PhCH_2CO_2^-$	buffer[b]	24	22	11	67
	CD_3CN	36	10	10	51
	CD_2Cl_2	40	16	9.3	56
	C_6D_6	48	31	6.8	47
HO^-	C_6D_6	nd[d]	0	97	0
PhO^-	buffer[b]	nd[d]	30	18	49
	C_6D_6	nd[d]	0	90	16

[a] Yields determined by ^1H NMR spectroscopy using DMSO as standard. [b] 50% D_2O in CD_3CN containing 100 mM phosphate buffer at pD 7. [c] Quantified by HPLC with added biphenyl as a standard and by ^1H NMR spectroscopy using DMSO as standard. [d] Not determined.

Chemical yields for photolyses of 10^{-2} M **4a** (LG^- = $PhCH_2CO_2^-$, HO^-, PhO^-) in various air-saturated solvents using Pyrex filtered light are collected in Table 1. The yields of **5a** were significantly lower than the yields of the released leaving group acid (LG^- = $PhCH_2CO_2^-$), evidently due to secondary photolysis of **5a**, which gave unidentifiable material exhibiting only broad peaks in ^1H NMR spectra.

Control experiments showed that neither of the lactams **6a** (LG^- = $PhCH_2CO_2^-$, BocAla) underwent dark reaction in 50% buffer in CD_3CN at pD 7 for over a week. This observation rules out a "dark" reaction that would diminish the yields of **6a**, such as solvolytic elimination of a leaving group, to afford **5a** or its isomer with an endocyclic double bond. Control experiments also showed that solutions of α-methylene lactam **5a** were unreactive in aq CD_3CN containing buffer at pD 7 in the dark for a period of one week. In solid form, however, **5a** slowly decomposed to form unidentifiable products, which gave only broad peaks in ^1H NMR spectra. Thus, all results requiring use of **5a** were obtained with fresh samples after chromatographic purification.

Preparative direct photolyses with Pyrex-filtered light of 0.005 M **4b** (LG^- = $PhCH_2CO_2^-$) in N_2 saturated 50% aq CH_3CN containing buffer at pH 7 for 2 h gave **5b** as the major photoproduct along with minor amounts of **6b** (LG^- = $PhCH_2CO_2^-$) in an ca. 2: 1 ratio. Whereas the cleavage coproduct could be isolated chromatographically, the minor lactam **6b** (LG^- = $PhCH_2CO_2^-$) was difficult to separate and therefore was obtained, independently, by acylation of allylic alcohol **6b** (LG^- = HO^-), which was produced upon preparative direct photolysis of **4b** (LG^- = HO^-) (Experimental Section). Similarly, direct photolysis of the phenolate derivative **4b** (LG^- = PhO^-) in buffer gave **5b** and **6b** in a 2:1 ratio, whereas in benzene, only lactam **6b** (LG^- = PhO^-) was obtained as a photoproduct.

TABLE 2. Chemical Yields[a] for Photolyses of 4b (LG^- = $PhCH_2CO_2^-$, HO^-, PhO^-) in Various Solvents

reactant, LG^-	solvent	LG-H, %	**5b**, %	**6b**, %	unreacted **4b**, %
$PhCH_2CO_2^-$	buffer[b]	71	53	25	5.4
	CD_2Cl_2	71	55	31	11
	C_6D_6	70	57	19	10
HO^-	buffer[b]	nd[c]	6.9	87	9.5
	CD_2Cl_2	nd[c]	9.9	84	5.8
PhO^-	buffer	nd[c]	45	20	36
	C_6D_6	nd[c]	0	85	10

[a] Yields determined by ^1H NMR spectroscopy using DMSO as standard. [b] 50% D_2O in CD_3CN containing 100 mM phosphate buffer at pD 7. [c] Not determined.

TABLE 3. Quantum Yields for Formation of Products from Direct Photolyses of 4a and 1b[a]

leaving group, LG^-	solvent	Φ (**5a**)	Φ (**6a**)
BocAla (pK_a 4.0[b])	buffer[c]	0.052	0.012
$PhCO_2^-$ (pK_a 4.2[b])	buffer[c]	0.032	0.0078
$PhCH_2CO_2^-$ (pK_a 4.3[b])	buffer[c]	0.031	0.011
PhO^- (pK_a 10[b])	buffer[c]	0.037	0.017
	C_6H_6	0	0.072
none (**1b**)	buffer[c]	na[d]	0.046 (**3b**)[e]
	C_6H_6	na[d]	0.083 (**3b**)[e]
	hexane	na[d]	0.077 (**3b**)[e]

[a] Average of two or more independent runs using ferrioxalate as actinometer; products were quantified by HPLC using the internal standard method to calibrate the 254 nm detector. [b] pK_a of the conjugate acid, see ref 18. [c] N_2 saturated 50% aq CH_3CN containing 100 mM phosphate buffer at pH 7. [d] Not applicable without a leaving group. [e] The product is **3b**.

When **5b** was stored in the dark as a solid, like **5a** (vide supra), a slow reaction was observed to give unknown products, which showed broad peaks in the ^1H NMR spectra. This "dark" reaction could be slowed substantially by storing **5b** as a dilute solution in 50% aq CH_3CN containing buffer. Nevertheless, all results requiring use of **5b** were obtained with fresh samples after chromatographic purification. A control experiment with lactam **6b** (LG^- = $PhCH_2CO_2^-$) showed it was stable for at least a week in 50% D_2O in CD_3CN containing buffer at pD 7 according to ^1H NMR analyses.

Preparative direct photolyses of 10^{-3}−10^{-2} M **1b**,**c** and **8a**,**b** in N_2-saturated 50% aq CH_3CN containing buffer at pH 7 gave lactams **3b**,**c**[2] (Scheme 1), **9a** (eq 1), and **9b** (eq 2) as the only product in each case (Experimental Section).

Quantum Yields. Quantum yields for products of **1b**,**c** and **4a**,**b** (Tables 3 and 4) were determined for photolyses in N_2 saturated 50% aq CH_3CN containing 100 mM phosphate buffer

TABLE 4. Quantum Yields for Formation of Products from Direct Photolyses of 4b and 1c[a]

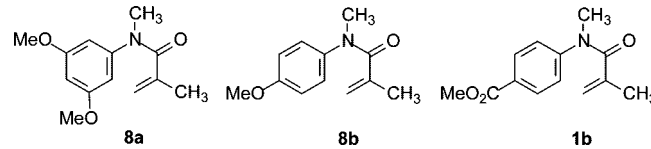
leaving group, LG^-	solvent	Additive	Φ (**5b**)	Φ (**6b**)
$PhCH_2CO_2^-$	buffer[c]	none	0.069	0.018
	buffer[c]	6.44×10^{-3} NPS[b]	0.070	0.017
	buffer	11.4×10^{-3} NPS[b]	0.075	0.021
PhO^-	buffer[c]	none	0.061	0.016
	C_6H_6	none	0	0.10
none (**1c**)	buffer[c]	none	na[d]	0.077 (**3c**)[e]
	buffer[c]	6.69×10^{-3} NPS[b]	na[d]	0.072 (**3c**)[e]
	buffer[c]	12.4×10^{-3} NPS[b]	na[d]	0.070 (**3c**)[e]
	20% aq CH_3CN	0.15 M *trans*-piperylene	na[d]	0.10 (**3c**)[e]

[a] Average of two or more independent runs using ferrioxalate as actinometer; products were quantified by HPLC using the internal standard method to calibrate the 254 nm detector. [b] Sodium 2-naphthalenesulfonate as the quencher. [c] N_2 saturated 50% aq CH_3CN containing 100 mM phosphate buffer at pH 7. [d] Not applicable without a leaving group. [e] The product is **3c**.

at pH 7 and in other solvents at low conversions to ascertain whether the leaving group eliminations occurred directly in the excited state or whether a ground-state intermediate such as the zwitterionic species **7a**,**b** was involved, which could partition between products **5a**,**b** and **6a**,**b** in ratios depending upon leaving group ability and solvent polarity, as implied by Scheme 2. As shown in Table 3, the quantum yields for **4a** are insensitive to the basicity of the leaving group, which argues against the elimination of the leaving group as occurring directly in the excited state. For the series of leaving groups of increasing basicity (LG^- = BocAla, $PhCO_2^-$, $PhCH_2CO_2^-$, PhO^-) the total quantum yields **5a** + **6a** measured for buffer as the solvent are nearly the same within experimental error to the quantum yield for formation of lactam **3b** from **1b**, which has no leaving group (Table 3 and Scheme 1, vide supra). The quantum yields are consistent with the ring-closure step as taking place in the excited state, prior to the elimination of the leaving group. The efficiency for excited-state electrocyclic ring closure is not expected to be influenced by the basicity of the leaving group. It is influenced, however, by the solvent. For example, the quantum yields for formation of lactam **3b** from **1b** in benzene or hexane are nearly twice those for aqueous buffer solutions as the medium.

The ratio of **5a**/**6a** is not markedly sensitive to leaving group basicity. Although the quantum yields for **4a** ($LG^- = PhO^-$) in buffer are very similar to those substrates with better leaving groups, when the solvent is changed to benzene, formation of lactam **6a** ($LG^- = PhO^-$) becomes the only reaction and elimination of the leaving group to form **5a** is not observed. Although we did not determine quantum yields for carboxylate leaving groups with benzene as solvent, product yields for **4a** ($LG^- = PhCH_2CO_2^-$) in Table 1 clearly show that, unlike the phenolate group, the carboxylate leaving group is photochemically released to give α-methylene lactam **5a** under both aqueous and nonaqueous conditions.

Substituent effects on quantum yields for reaction were explored for **8a**,**b** (eqs 1 and 2) for comparison to **1b** (Scheme 1). The electron-donating methoxy substituents and the existant acrylamide nitrogen should be capable of transmitting electron density to the ortho and meta positions of the aromatic ring in the excited state,[14,15] which, a priori, could result in a more efficient electrocyclization step. However, for photolyses in 50% aq CH_3CN containing buffer, the quantum yield for the *meta*-dimethoxy compound **8a** is essentially identical to **1b**, whereas *para*-methoxy substitution in **8b** causes the quantum yield to decrease.



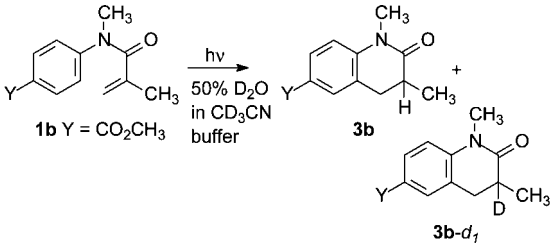
8a Φ = 0.050 **8b** Φ = 0.029 **1b** Φ = 0.046

Quantum yields for direct photolysis of the benzoyl-substituted anilide **4b** ($LG^- = PhCH_2CO_2^-$, PhO^-) (Table 4) are significantly higher than those for **4a**. Regardless of the leaving group, the total quantum yields for products (**5a** + **6b**) are nearly the same as the quantum yield for formation of **3c** from **1c**, which has no leaving group, consistent with the electrocyclic ring closure step as governing the efficiency of the reaction. Like **4a** ($LG^- = PhO^-$), the ratio of **5b**/**6b** formed from **4b** ($LG^- = PhO^-$) is solvent dependent, which supports the involvement of a ground-state intermediate in the photochemistry. The photorelease of the phenolate group to give α-methylene lactam **5b** strongly predominates in buffer, whereas in nonpolar aprotic solvent the intermediate instead rearranges to lactam **6b**. The overall photoreaction is also somewhat more efficient in a nonpolar solvent, such as benzene, as compared to aqueous media.

The photochemical reactions of **1c** and **4b** are not quenched by the water-soluble triplet quencher, sodium 2-naphthalenesulfonate in buffer, or by *trans*-piperylene (Table 4) in aq CH_3CN. The longer-wavelength absorptions of **1c** and **4b** permit photolyses to be conducted at 365 nm in the presence of the quenchers, which absorb light at much shorter wavelengths. The triplet energy, E_T, of **1b** and **4b** should be close to 68 kcal/mol, while E_T of sodium naphthalene sulfonate is assumed to be similar to naphthalene (ca. 61 kcal/mol[20]). Thus, the quenching of the triplet excited states of **1c** and **4b** is expected to proceed via diffusion-controlled energy transfer. The laser flash photolysis experiments with **1c** and **4b** (vide infra) further show that the triplet excited states are quenched at similar or lower concentrations of the sodium 2-naphthalenesulfonate than used in the steady-state quenching experiments (Table 4). Therefore, the singlet excited-state is the reactive excited-state in the formation of products from **1c** and **4b**.

Deuterium Labeling. Deuterium labeling experiments were performed with **1b** to determine whether a ground-state intermediate can be intercepted by protic solvent to form lactam **3b** containing deuterium (Scheme 1). Photolyses of **1b** in 50% D_2O in CD_3CN containing 100 mM phosphate buffer at pD 7 as the solvent resulted in incorporation of deuterium into lactam **3b** to an extent of 74%, according to ^1H NMR spectroscopy and GC-MS analysis (eq 4). A control experiment showed that undeuterated lactam **3b** does not undergo significant hydrogen−deuterium exchange under the reaction conditions. Thus, for photolyses in protic solvents or aqueous media, much of the lactam **3b** is expected to be produced via a mechanism involving proton transfer from the protic solvent to an intermediate with enolate character, e.g., zwitterion **2b**, whereas the 1,5-H shift in zwitterionic intermediate **2b** makes a smaller contribution to the formation of lactam **3b**.

(18) (a) pK_a values: Rappoport, Z. *CRC Handbook of Tables for Organic Compound Identification*, 3rd ed.; Weast, R. C., Ed.; CRC: Cleveland, 1967; pp 429−435. (b) BocAlaOH, pK_a 4.02, CA 15761-38-3.



(4)

Laser Flash Photolyses. Laser flash photolysis experiments were conducted with **1c** and **4b** ($LG^- = HO^-$, $PhCH_2CO_2^-$) at 355 nm in 50% aq CH_3CN containing 100 mM phosphate buffer at pH 7. Each degassed sample under argon gave a transient absorption with a maximum in the 450−550 nm region with additional bands extending to 700 nm, which was attributed to the triplet excited-state of each anilide (Figure 2). The lifetime of the decay of the transient was essentially identical for the three compounds: **1c**, $\tau = 335$ ns; **4b** ($LG^- = HO^-$), $\tau = 358$ ns; **4b** ($LG^- = PhCH_2CO_2^-$), $\tau = 356$ ns. In addition, the lifetimes for decay were essentially the same at other wavelengths over the 450−700 nm wavelength range.

The transient absorption spectrum of **1c**, **4b** ($LG^- = HO^-$), and **4b** ($LG^- = PhCH_2CO_2^-$) exhibited linear Stern−Volmer quenching kinetics upon addition of the triplet excited-state quencher, sodium 2-naphthalene sulfonate (Figure 3). For **1c**, **4b** ($LG^- = HO^-$), and **4b** ($LG^- = PhCH_2CO_2^-$), the respective slopes were $k_q = 3.77 \times 10^9$ M^{-1} s^{-1}, 2.73×10^9 M^{-1} s^{-1}, and 4.34×10^9 M^{-1} s^{-1}, consistent with quenching of the lowest triplet excited state of each compound by triplet energy transfer to the quencher.

Compound **1c** shows weak fluorescence in the 370−500 nm region according to steady-state experiments. However, the fluorescence efficiency in CH_3CN is estimated to be low ($\Phi_f < 0.01$) by comparison to the fluorescence of quinine bisulfate ($\Phi_f = 0.55$) as a standard.[21] The low quantum yield is consistent with the previous report of inefficient fluorescence of analogous amide derivatives of *p*-aminobenzophenone.[19] Fluorescence is also observed in the above laser flash photolysis experiments. For both **1c** and **4b** ($LG^- = PhCH_2CO_2^-$), the fluorescence decay lifetimes were measured at various wavelengths over a 420−470 nm range and found to be less than the duration of the laser flash ($\tau < 10$ ns).

Triplet Yields. Considering the likelihood that the photoreactivity of **1c** and **4b** originates from the singlet excited state, according to the above quenching experiments, it became important to determine the efficiency of intersystem crossing as a process that would compete with reaction in the singlet excited state. Quantum yields for intersystem crossing, Φ_{isc}, were measured for **1c** using literature procedures,[22] which involved quenching of its triplet excited-state by *trans*-piperylene and determining the extent of *trans*−*cis* isomerization of the 1,3-diene quencher for a given amount of light absorbed. The

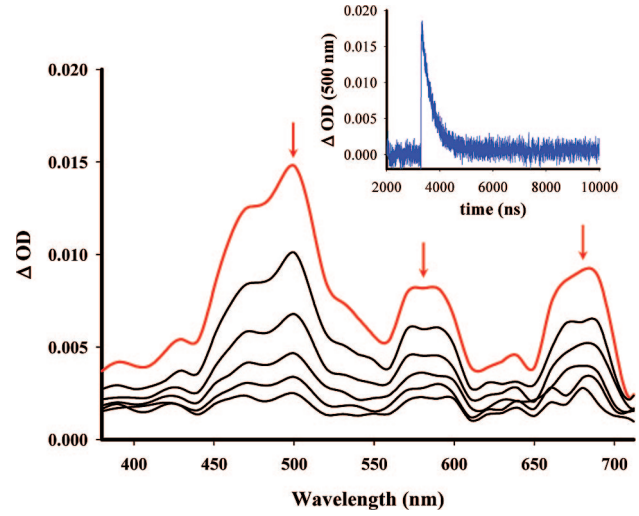


FIGURE 2. Transient triplet absorption spectrum produced upon laser flash photolysis of 2.5 mM **1c** in 50% aq CH_3CN containing 0.1 M phosphate buffer at pH 7 following 10 ns laser excitation at 355 nm. The spectral bands at 500 nm, 580 nm, and 670 nm showed identical decay lifetimes ($\tau = 335$ ns).

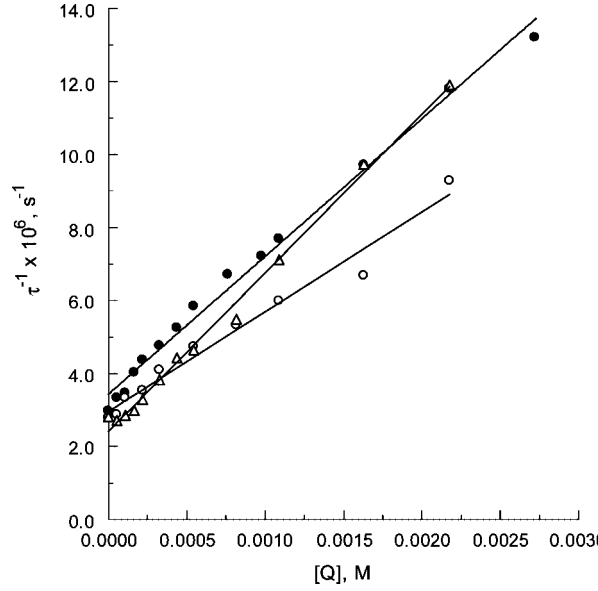
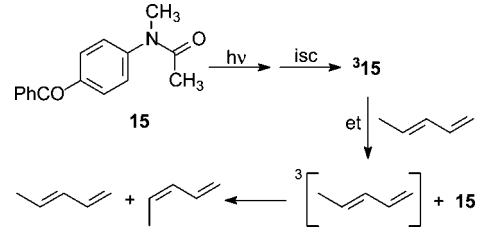


FIGURE 3. Stern−Volmer plot of $^3\tau^{-1}$ for **1c** (●), **4b** ($LG^- = HO^-$, Δ), and **4b** ($LG^- = PhCH_2CO_2^-$, ○) vs concentration of sodium 2-naphthalenesulfonate used as quencher, Q.

SCHEME 5



experiments were performed with benzophenone, compound **1c**, and additionally the *N*-acetyl derivative of 4-(methylamino)benzophenone **15** (Scheme 5), which does not undergo photochemical reaction.

In benzene, the acetamide **15** undergoes intersystem crossing ($\Phi_{isc} = 0.93$) almost as efficiently as benzophenone ($\Phi_{isc} =$

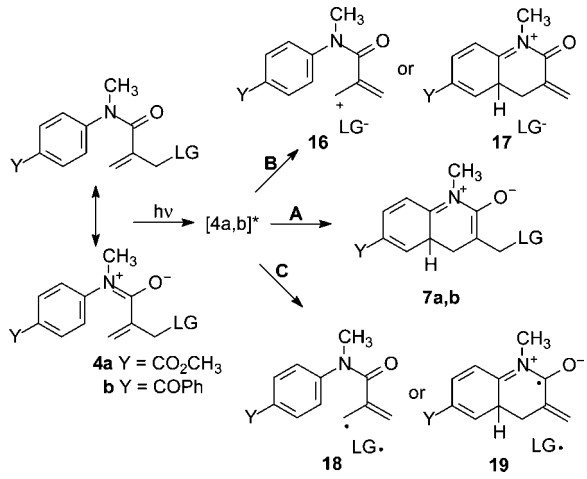
(19) Allen, N. S.; Salleh, N. G.; Edge, M.; Corrales, T.; Shah, M.; Weddell, I.; Catalina, F.; Green, A. *J. Photochem. Photobiol. A: Chem.* **1996**, *99*, 191–196.

(20) Murov, S. L.; Carmichael, I.; Hug, G. L. *Handbook of Photochemistry*, 2nd ed.; Marcel Dekker: New York, 1993; pp 30−31.

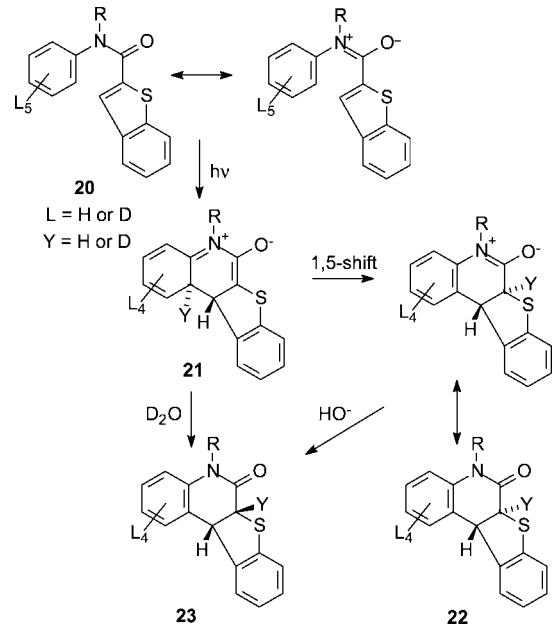
(21) (a) Meech, S. R.; Phillips, D. *J. Photochem.* **1983**, *23*, 193–217. (b) Hamai, S.; Hirayama, F. *J. Phys. Chem.* **1983**, *87*, 83–89. (c) Melhuish, W. H. *J. Phys. Chem.* **1961**, *65*, 229–235. (d) Eaton, D. F. In *Handbook of Organic Photochemistry*; Scaiano, J. C., Ed.; CRC Press: Boca Raton, FL, 1989; Vol. I , Chapter 8.

(22) (a) Lamola, A. A.; Hammond, G. S. *J. Chem. Phys.* **1965**, *43*, 2129–2135. (b) See ref, 20 pp 310−312.

SCHEME 6



SCHEME 7



1.00[20]), and the efficiency remains similarly high in going to the polar solvent, 21% aq CH_3CN, for which Φ_{isc} (**15**) = 0.95. For the α,*β*-unsaturated anilide **1c**, the quantum yields are considerably lower, $\Phi_{isc} = 0.20$ in benzene and $\Phi_{isc} = 0.15$ in 20% aq CH_3CN. In the presence of the 0.15 M *trans*-piperylene, the quantum yield for photorearrangement of **1c** to give **3c** was 0.10 in 20% aq CH_3CN, and thus the photorearrangement is not quenched under conditions whereby energy transfer to *trans*-piperylene results in *trans*−*cis* isomerization. Thus, the triplet yields do not vary significantly with solvent polarity, and for **1c**, intersystem crossing is not a highly efficient decay pathway of the singlet excited state.

Discussion

The principal excited-state reaction of **4a**,**b** is thought to be electrocyclic ring closure to give **7a**,**b** as an intermediate (Scheme 2 and path A in Scheme 6). The quantum efficiencies for the excited-state ring closure are not sensitive to the nature of the remote leaving groups in **4a**,**b**.

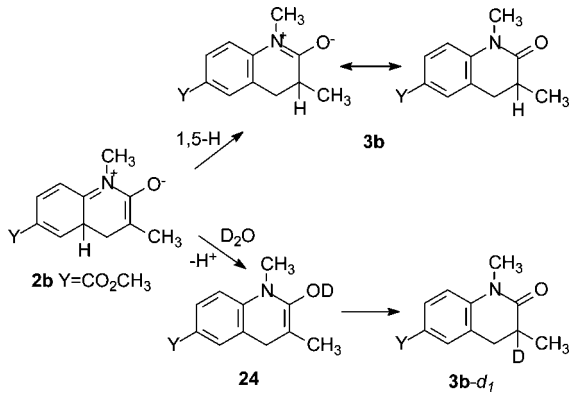
The overall quantum yields for reaction of **4a**,**b** to give **5a**,**b** + **6a**,**b** are very similar to those observed for the photocyclization of the para-substituted derivatives **1b**,**c** (Tables 3 and 4), which have no leaving groups and can only photocyclize to lactams **3b**,**c** (Scheme 1). These results are contrary to what would be expected if the leaving groups were expelled as anions directly in the excited states of **4a**,**b** (path B, Scheme 6). In the excited-state eliminations, the quantum yields should decrease with increasing basicity of the leaving group expelled because the anion expulsions would be competing with rapid decay processes of the excited state. Homolytic cleavage of the leaving groups in the excited-state is considered to be unlikely (path C, Scheme 6) because in the case of **4a**,**b** ($LG^- = PhCH_2CO_2^-$) radical byproducts, such as toluene or bibenzyl, are not observed from decarboxylation of the α-phenylacetyloxyl radical,[23] which should also have led to low yields of the photochemically released phenylacetic acid (Tables 1 and 2). Homolysis might occur in the triplet excited-state. However, the laser flash photolysis experiments show that the lifetimes of the transient absorption attributable to the triplet excited-state are essentially invariant for the series of compounds **1c**, **4b** ($LG^- = HO^-$), and **4b** ($LG^- = PhCH_2CO_2^-$), which have widely differing types of allylic substituents.

The results of our study of the photochemistry of **4a**,**b** are consistent with zwitterions **7a**,**b** as playing an important role as intermediates involved in the formation of elimination products **5a**,**b** and lactams **6a**,**b** (Scheme 2). Similarly, zwitterionic intermediates **2b**,**c** would be expected to be the key intermediates in the formation of lactams **3b**,**c** from anilides **1b**,**c** (Scheme 1). The photochemical ring closure of anilides **1b**,**c** and **4a**,**b** should produce these intermediates via an excited-state allowed conrotatory electrocyclic ring closure reaction. Such a ring closure would be consistent with the mesomeric nature of the amide group, which should have significant double bond character between the carbonyl group and amide nitrogen. Although our study provides no information on the stereochemistry of the ring closure step itself, previous studies support such a conrotatory mode of ring closure.[5,6] An example is provided by the photochemistry of **20**-d_5 (L = D) under aprotic conditions (Scheme 7).[6] In this case, a conrotatory ring closure step, which produces **21** (Y = D), would be needed to account for the stereochemistry of deuterium in the trans-fused product **22** (Y = D) since the second step of the reaction should be a thermally allowed, suprafacial 1,5-D shift.

In protic solvents, the 1,5-H shift may not be the sole mechanism for the formation of lactams **3a**−**c** and **6a**,**b** from photolysis of **1a**−**c** and **4a**,**b**. The other mechanism involves a proton transfer from protic solvent at some stage in the conversion of the zwitterionic intermediates **2a**−**c** and **7a**,**b** to lactam products. Such a proton transfer to form enol **24** evidently occurs upon photolysis of **1b** (Scheme 8) in CD_3CN containing 50% phosphate buffer in D_2O at pD 7, given the observed extensive incorporation of deuterium into the α-position of **3b**. In CD_3CN containing 50% buffer in D_2O (pD 7), the lactam **3b** does not undergo H/D exchange in the dark. According to the literature,[6] if a protic solvent is used in the photolysis of **20** (L = H), then the major product becomes the cis-fused isomer **23** rather than **22** (Scheme 7). External deuterium is incorporated into **23** (Y = D) from the solvent when undeuterated **20** (L = H) is photolyzed in 10% D_2O in acetonitrile. This deuterated

(23) (a) Hilborn, J. W.; Pincock, J. A. *J. Am. Chem. Soc.* **1991**, *113*, 2683–2686. (b) Pincock, J. A. *Acc. Chem. Res.* **1997**, *30*, 43–49. (c) Banerjee, A.; Falvey, D. E. *J. Am. Chem. Soc.* **1998**, *120*, 2965–2966.

SCHEME 8



product, formed in 34% yield, is accompanied by 28% of unlabeled trans-fused product **22**, produced via the 1,5-H shift in zwitterionic intermediate **21** (L = H, Y = H). The formation of **23** upon protonation of **21** probably involves an enol intermediate. The cis-fused isomer **23** is more stable than trans-fused compound **22** (Y = H), which would be consistent with the base epimerization of **22** (Y = H) to **23** (Y = H).

The singlet excited-state has experimental support as the reactive excited-state in the photochemistry of **1c** and **4b**. The failure to quench the photochemistry of **1c** and **4b** suggests that the triplet excited-state is not involved in the photochemistry of these two cases. The quantum yields for lactam **3b** and for products **5b** and **6b** are unchanged, when the photolyses are conducted with the triplet excited-state quencher, sodium 2-naphthalenesulfonate, whereas the laser flash photolysis experiments show that the transient absorption assigned to the triplet excited-state is quenched at the same or lower concentrations of quencher. While these results support the singlet excited-state in the reaction, the quantum yields for reaction of **1c** and **4b** are relatively low, $\Phi_r < 0.1$, and only weak fluorescence is observed with **4b** ($\Phi_f < 0.01$). Therefore, the singlet excited-state primarily deactivates to the ground-state via other processes besides product formation and fluorescence. Other possible deactivating processes of the singlet excited-state are intersystem crossing and nonproductive radiationless decay to regenerate ground-state reactant. Of these processes, the latter makes the larger contribution, since intersystem crossing accounts for only 15% of the singlet excited-state decay of **1c**. This relatively low triplet yield for **1c** is somewhat surprising, considering that intersystem crossing accounts for 93% of the singlet excited-state decay of the anilide model compound **15** (Scheme 5).[24] The total rate of decay of **1c**, as well as **4b** ($LG^- = HO^-$, $PhCH_2CO_2^-$) is estimated to be at least 10^8 s^{-1}, since the singlet lifetimes measured in the laser flash photolysis experiments are found to be less than the duration of the laser flash of ca. 10 ns. For a quantum yield of reaction of 0.07−0.09 for **1c** and **4b**, the rate constant for electrocyclization is estimated to be at least ca. 10^6-10^7 s^{-1}, if the electrocyclization step is irreversible such that the initially formed zwitterionic intermediates do not undergo disrotatory ring opening to regenerate ground-state reactants.

It seemed possible to increase the rate of cyclization relative to singlet excited-state decay by use of substituents attached to the aromatic ring of **1a**−**c**. Disubstitution of hexatrienes, for example, has been shown to dramatically enhance rates for electrocyclic ring closure in the ground state, depending on the substituents.[25] To our knowledge, a similar systematic study of substituent effects on the excited-state electrocyclic reaction has not been reported, however. Our attempt to increase the rates of cyclization and hence quantum yields by introducing *meta*- or *para*-methoxy groups resulted in no change in efficiency or even decreased efficiency with derivatives **8a**,**b**.

Nonproductive radiationless decay to regenerate reactants is evidently the principal process for the decay of the singlet excited states of **1c** and **4b**. We therefore have considered the possibility that the radiationless decay process could be due to a reversible photocyclization step whereby the initially formed zwitterionic intermediates, **2c** and **7b**, rapidly revert to ground-state reactants. If the leaving groups are expelled directly from the zwitterionic intermediate **7b**, rapid regeneration of ground-state reactant upon disrotatory ring opening of the zwitterionic intermediates should result in decreased quantum yields for **5b** as well as decreased total quantum yields for products **5b** + **6b** as the basicity of the leaving group increases. Experimentally, these quantum yields are found to be insensitive to leaving group effects (vide supra). Similar reasoning would argue against a reversible electrocyclization step to form **7a** from **1a** since the total quantum yields for **5a** + **6a** are unaffected by leaving groups having a wide range of basicities.

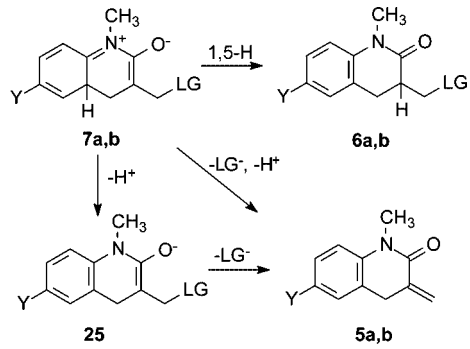
In the case of **4a**, the product ratio **6a**/**5a** should increase with increasing basicity of the leaving group as a consequence of the partitioning of **7a** between these two products, according to Scheme 2. However, very little variation in product ratio is observed in polar solvent (50% buffer in CH_3CN) as the leaving group is varied. The insensitivity of product ratio to leaving group ability is rather similar to what was observed for α-keto amide photochemistry,[8] for which the zwitterionic intermediate exclusively expelled both carboxylate and the more basic phenolate group, as long as the photolyses were conducted in an aqueous medium. As in our earlier study, it proved possible with $LG^- = PhO^-$ to influence the relative rate of leaving group release vs cyclization of the zwitterion by changing the solvent from buffer in aq CH_3CN to a nonpolar solvent, such as benzene. In the case of **4a**,**b** ($LG^- = PhO^-$), the product ratio favors elimination of the leaving group to give **5a**,**b** in polar solvent but reverses in favor of formation of **6a**,**b** in the nonpolar solvent, benzene.

Although our previous work[7,8] shows that all of the leaving groups studied herein can be expelled directly from zwitterionic intermediates that are similar to **7a**,**b**, there is an alternate mechanism to be considered for **4a**,**b**, which involves initial loss of a proton from zwitterions **7a**,**b** followed by expulsion of the leaving group from the enolate **25** (Scheme 9). The alternate mechanism better accounts for the insensitivity of the observed **5a**,**b**/**6a**,**b** product ratios as the leaving group basicity

(24) (a) The reason for the lower Φ_{isc} of unsaturated amide **1c** as compared to the acetanilide **15** is not obvious. It could be due to more rapid competing radiationless decay of S_1 to S_0 for **1c**, perhaps due to the presence of the unconstrained double bond. However, the actual reason could be more complicated.[24b] The S_1 radiationless decay mechanism is not understood. Alternatively, rate constants for intersystem crossing could be lower due to an energy mismatch of the S_1 excited state and a corresponding triplet excited state, or the energetically proximate triplet excited state might have the same electronic configuration.[24c] There does seem to be some degree of quenching of the singlet excited state by protic solvent, which has precedent.[24d] The solvent effects on the quantum yield data suggest that such quenching is more pronounced for **4a** than **4b**, but solvent effects do not account for the difference in Φ_{isc} between **1c** and **15**. (b) Biczok, L.; Berces, T.; Marta, F. *J. Phys. Chem.* **1993**, *97*, 8895–8899. (c) Schuster, D. I.; Goldstein, M. D.; Bane, P. *J. Am. Chem. Soc.* **1977**, *99*, 187–193. (d) Yatsuhashi, T.; Nakajima, Y.; Shimada, T.; Tachibana, H.; Inoue, H. *J. Phys. Chem.* **1998**, *102*, 8657–8663.

(25) Yu, T.-Q.; Fu, Y.; Liu, L.; Guo, Q.-X. *J. Org. Chem.* **2006**, *71*, 6157–6164.

SCHEME 9



varies.[26] Accordingly, the 2.2−4.1:1 ratio of **5a**,**b**/**6a**,**b** for the leaving groups would largely be established by the competition between the 1,5-H shift and the deprotonation of the zwitterion. It nevertheless seems reasonable to expect that direct elimination of the leaving groups from **7a**,**b** contributes to varying extent, depending on leaving group basicity and the solvent, to the formation of **5a**. According to Scheme 9, the exclusive formation of **6a**,**b** ($LG^- = PhO^-$) from **4a**,**b** ($LG^- = PhO^-$) in benzene would be explained by a slowed rate of PhO^- release and a suppressed rate of proton release from **7a**,**b**, in which case the carboxylate leaving groups would be expelled directly from the zwitterions to form an ion-pair intermediate (Tables 1 and 2).

The mechanism in Scheme 9 makes it possible to reconsider the possibility that **7a**,**b** are photochemically generated in a reversible step such that they undergo disrotatory ring opening in the ground-state to regenerate reactants **4a**,**b**. It is difficult to say whether such a reversible electrocyclization step could account for the rapid radiationless decay of the singlet excited states of **1c** and **4b** and the relatively low quantum yields for products. Alternatively, rapid excited-state decay could be due to rotation about the 1,1-disubstituted double bond of the α,β-unsaturated amides, although this remains to be tested experimentally.

Conclusions

α,β-Unsaturated anilides bearing leaving groups at the allylic position of the α-methylacrylamide group undergo photochemical electrocyclic ring closure with release of the leaving group to form an α-methylene lactam. Under aqueous conditions, leaving groups spanning a wide range of basicities from carboxylate groups to phenolate groups can be expelled with little loss in efficiency as the leaving group is varied. For the *para*-carbomethoxy-substituted anilides, the efficiencies for leaving group release are Φ = ca. 0.04 at a wavelength of 310 nm. Higher efficiencies (Φ = ca. 0.07) for leaving group expulsion are observed for a *para*-benzoyl derivative of the anilide, in which case the photolysis wavelength can be routinely extended to 365 nm. The photochemistry is proposed to involve photochemically allowed electrocyclization to produce a ground-state zwitterionic intermediate. Leaving group release could occur directly from this intermediate or via an enolate produced upon deprotonation of the zwitterionic intermediate. An accompanying minor photoproduct is a lactam, which retains the leaving group. This lactam is thought to be formed via a 1,5-H shift of the zwitterionic intermediate and could also be formed upon protonation of the zwitterion in protic solvent. The photochemistry derives from the singlet excited state. The singlet excited-state otherwise undergoes mainly rapid radiationless deactivation to the ground state and, according to the results with **1c**, intersystem crossing to the triplet excited-state with $\Phi_{isc} = 0.15-0.20$. The triplet excited-state cannot account for the photochemistry of **1c** and **4b**. The triplet excited-state is strongly quenched by energy transfer to efficient triplet quenchers, according to the laser flash photolysis studies, whereas quantum yields for products remain unaffected at the same or lower concentrations of the quencher used to quench the transient absorption of the triplet excited state, observed in the laser flash photolysis studies.

(26) We thank a referee for proposing the alternate mechanism.

Experimental Section

Preparative chromatographic separations used a 2.5 cm × 28 cm column packed with 230−400 mesh silica gel (Sorbent technologies), eluting with the specified solvent at a flow rate of 15 mL/min using a pump. HPLC analysis was performed using a 4.6 × 250 mm column of YMC ODS-AQ S-5 120 Å (Waters) at a flow rate of 1 mL/min with 30−40% aqueous acetonitrile as the mobile phase.

Preparation of Methyl 4-[[2-(Hydroxymethyl)acryloyl]methylamino]benzoate (4a, $LG^- = HO^-$). The procedure was adapted from the literature.[16] To a mixture of 35 g (0.16 mol) of **11a** and 350 mL of THF was added 350 mL of a 40% aqueous formaldehyde and 35 g (0.31 mol) of DABCO. The suspension was sonicated for 48 h at 50−60 °C. The mixture was extracted with ethyl acetate. The extracts were washed with saturated $NaHCO_3$ and brine and dried over anhydrous sodium sulfate. Concentration in vacuo followed by chromatography on silica gel, eluting with 25% ethyl acetate in hexane, gave 16 g (0.064 mol, 40% yield) of compound **4a** ($LG^- = HO^-$) as a colorless crystalline solid, mp 82−83 °C. The spectral data were as follows: ^1H NMR ($CDCl_3$) δ 3.37 (s, 3H), 3.88 (s, 3H), 4.21 (s, 2H), 4.93 (s, 1H), 5.28 (s, 1H), 7.26 (d, J = 8.0 Hz, 2H), 7.98 (d, J = 8.0 Hz, 2H); ^{13}C NMR ($CDCl_3$) δ 37.8, 52.5, 64.3, 120.6, 126.5, 128.7, 130.9, 143.2, 148.7, 166.4, 170.6. Anal. Calcd for $C_{13}H_{15}NO_4$: C, 62.64%; H, 6.07%; N, 5.62%. Found: C, 62.71%; H, 6.06%; N, 5.62%.

Preparation of Methyl 3-(Hydroxymethyl)-1-methyl-2-oxo-1,2,3,4-tetrahydroquinoline-6-carboxylate (6a, $LG^- = HO^-$) by Photolysis of 4a ($LG^- = HO^-$). A solution of 0.37 g (2.0 mmol) of **4a** ($LG^- = HO^-$) in N_2 saturated 250 mL of benzene containing several crystals of *p*-methoxyphenol as a radical inhibitor was irradiated with a 450 W Hanovia medium pressure mercury lamp in an immersion well apparatus for 7.5 h with stirring. The solvent was removed in vacuo, and the residue was chromatographed on silica gel, eluting with 20% ethyl acetate in hexane, to obtain 0.31 g (1.2 mmol, 83% yield) of colorless crystalline product, mp 117−120 °C. The spectral data were as follows: ^1H NMR ($CDCl_3$) δ 2.66−2.97 (br m, 3H), 3.41 (s, 3H), 3.92 (br s, 6H), 7.04 (d, J = 8.4 Hz, 1H), 7.88 (s, 1H), 7.97 (dd, J = 2.1, 8.4 Hz, 1H); ^{13}C NMR ($CDCl_3$) 27.7, 29.8, 42.2, 52.2, 62.5, 114.5, 124.7, 125.4, 129.3, 129.5, 143.6, 166.5, 172.5. Anal. Calcd for $C_{13}H_{15}NO_4$: C, 62.64%; H, 6.07%; N, 5.62%. Found: C, 62.97%; H, 6.04%; N, 5.70%.

Preparation of Methyl 4-[{2-[(Benzoyloxy)methyl]acryloyl}-(methyl)amino] Benzoate (4a, $LG^- = PhCOO^-$). To a solution of 0.80 g (3.2 mmol) of **4a** ($LG^- = HO^-$) and 0.45 mL of triethylamine in 10 mL of CH_2Cl_2 at 0 °C was added, dropwise with stirring, 0.38 mL (3.3 mmol) of benzoyl chloride in 10 mL of CH_2Cl_2. The reaction was stirred overnight at room temperature. The reaction mixture was washed with 5% $NaHCO_3$ and brine. After drying over $MgSO_4$, the solvent was removed in vacuo, and the residue was chromatographed on silica gel, eluting initially with 10% ethyl acetate in hexane to elute two minor impurities and then 40% ethyl acetate in hexane to elute an impurity and to obtain 0.77 g (2.2 mmol) of **4a** ($LG^- = PhCOO^-$) as a colorless oil. The

chromatography was repeated to obtain a colorless solid, mp 62−64 °C. The spectral data were as follows: ^{1}H NMR ($CDCl_3$) δ 3.42 (s, 3H), 3.90 (s, 3H), 4.95 (s, 2H), 5.18 (s, 1H), 5.49 (s, 1H), 7.24 (d, J = 8.0 Hz, 2H), 7.47 (d, J = 7.8 Hz, 2H), 7.59 (t, J = 7.8 Hz, 1H), 7.95 (d, J = 8 0.0 Hz, 2H), 8.05 (d, J = 7.8 Hz, 2H); ^{13}C NMR ($CDCl_3$) 37.9, 52.5, 65.0, 123.2, 126.4, 128.7, 129.8, 129.9, 130.3, 130.9, 133.5, 139.1, 148.5, 166.1, 166.4, 168.9. Anal. Calcd for $C_{20}H_{19}NO_5$: C, 67.98%; H, 5.42%; N, 3.96%. Found: C, 67.93%; H, 5.52%; N, 4.13%.

Preparation of Methyl 3-[(Benzoyloxy)methyl]-1-methyl-2-oxo-1,2,3,4-tetrahydroquinoline-6-carboxylate (6a, LG$^-$ = PhCOO$^-$). To a solution of 0.19 g (0.78 mmol) of **6a** (LG$^-$ = HO$^-$) and 0.15 mL of triethylamine in 10 mL of CH_2Cl_2 at 0 °C was added, dropwise with stirring, 0.11 mL (0.78 mmol) of benzoyl chloride in 10 mL of CH_2Cl_2. The reaction was stirred overnight at room temperature. The reaction mixture was washed with 5% $NaHCO_3$ and brine. After drying over Na_2SO_4, the solvent was removed in vacuo and the residue was chromatographed on silica gel, eluting with 10% ethyl acetate in hexane, to obtain 0.23 g (0.65 mmol, 84% yield) of colorless crystalline product, mp 127−131 °C. The spectral data were as follows: ^{1}H NMR ($CDCl_3$) δ 2.98−3.16 (br m, 3H), 3.40 (s, 3H), 3.88 (s, 3H), 4.57 (dd, J = 6.15, 11.1 Hz, 1H), 4.77 (dd, J = 3.81, 11.1 Hz, 1H), 7.01 (d, J = 8.52 Hz, 1H), 7.41 (t, J = 7.8 Hz, 2H), 7.54 (t, J = 7.8 Hz, 1H), 7.87 (s, 1H), 7.97−7.93 (m, 3H); ^{13}C NMR ($CDCl_3$) 28.7, 30.2, 40.2, 52.3, 63.9, 114.6, 124.8, 124.8, 128.6, 129.5, 129.8, 130.0, 133.3, 144.1, 166.5, 166.6, 169.7. Anal. Calcd for $C_{20}H_{19}NO_5$: C, 67.98%; H, 5.42%; N, 3.96%. Found: C, 68.06%; H, 5.58%; N, 3.99%.

Preparation of Methyl 4-[{2-[(Phenylacetyloxy)methyl]acryloyl}(methyl)amino]benzoate (4a, LG$^-$ = PhCH$_2$COO$^-$). To a solution of 1.0 g (4.0 mmol) of **4a** (LG$^-$ = HO$^-$) and 0.56 mL of triethylamine in 10 mL of CH_2Cl_2 at 0 °C was added, dropwise with stirring, 0.56 mL (4.2 mmol) of phenylacetyl chloride in 10 mL of CH_2Cl_2. The reaction was stirred overnight at room temperature. The reaction mixture was washed with 5% $NaHCO_3$ and brine. After drying over Na_2SO_4, the solvent was removed in vacuo, and the residue was chromatographed on silica gel, eluting with 10% ethyl acetate in hexane to obtain 1.4 g (3.8 mmol, 95% yield) of NMR pure **4a** (LG$^-$ = PhCH$_2$COO$^-$) as a colorless oil. The spectral data were as follows: ^{1}H NMR ($CDCl_3$) δ 3.27 (s, 3H), 3.62 (s, 2H), 3.85 (s, 3H), 4.63 (s, 2H), 4.97 (s, 1H), 5.22 (s, 1H), 6.95 (d, J = 7.2 Hz, 2H), 7.19−7.28 (m, 5H), 7.84 (d, J = 7.2 Hz, 2H); ^{13}C NMR ($CDCl_3$) 37.8, 41.6, 52.5, 65.4, 126.4, 127.5, 128.7, 128.9, 128.9, 129.6, 130.9, 133.9, 138.9, 148.4, 166.4, 168.6, 170.9. Anal. Calcd for $C_{21}H_{21}NO_5$: C, 68.65%; H, 5.76%; N, 3.81%. Found: C, 68.44%; H, 5.82%; N, 4.00%.

Preparation of Methyl 1-Methyl-2-oxo-3-(phenylacetyloxymethyl)-1,2,3,4-tetrahydroquinoline-6-carboxylate (6a, LG$^-$ = PhCH$_2$COO$^-$). To a solution of 0.25 g (1.0 mmol) of **6a** (LG$^-$ = HO$^-$) and 0.14 mL of triethylamine in 10 mL of CH_2Cl_2 at 0 °C was added, dropwise with stirring, 0.14 mL (1.1 mmol) of phenylacetyl chloride in 5 mL of CH_2Cl_2. The reaction was stirred overnight at room temperature. The reaction mixture was washed with 5% $NaHCO_3$ and brine. After drying over Na_2SO_4, the solvent was removed in vacuo, and the residue was purified on silica gel, eluting with 10% ethyl acetate in hexane on silica gel to obtain 0.32 g (0.87 mmol, 87% yield) of colorless crystalline product, mp 48−51 °C. The spectral data were as follows: ^{1}H NMR ($CDCl_3$) δ 2.78−2.93 (br m, 3H), 3.37 (s, 3H), 3.62 (s, 2H), 3.92 (s, 3H), 4.33 (dd, J = 6.12, 11.22 Hz, 1H), 4.56 (dd, J = 4.08, 11.22 Hz, 1H), 7.00 (d, J = 8.40 Hz, 1H), 7.26−7.34 (m, 5H), 7.78 (s, 1H), 7.95 (dd, J = 2.01, 8.04 Hz, 1H); ^{13}C NMR ($CDCl_3$) 28.3, 30.1, 40.0, 41.4, 52.5, 63.5, 114.5, 124.8, 127.4, 128.8, 129.4, 129.4, 129.4, 129.7, 134.0, 144.0, 166.6, 169.6, 171.5. Anal. Calcd for $C_{21}H_{21}NO_5$: C, 68.65%; H, 5.76%; N, 3.81%. Found: C, 68.86%; H, 5.74%; N, 3.77%.

Preparation of Methyl 4-{methyl[2-(phenoxymethyl)acryloyl]amino}benzoate (4a, LG$^-$ = PhO$^-$). The procedure is similar to that reported previously.[17] To a solution of 1.0 g (4.0 mmol) of **4a** (LG$^-$ = HO$^-$), 0.57 g (6.0 mmol) of phenol, and 1.3 g (4.81 mmol) of PPh_3 in 20 mL of dry THF was added 0.76 mL (4.8 mmol) of diethyl azodicarboxylate dropwise at 0 °C under N_2. The reaction mixture was then stirred at room temperature for 24 h and was concentrated in vacuo. The residue was chromatographed on silica gel, eluting with 10% ethyl acetate in hexane, to give 0.52 g (1.6 mmol, 40%) of NMR pure **4a** (LG$^-$ = PhO$^-$) as a colorless oil. The spectral data were as follows: ^{1}H NMR ($CDCl_3$) δ 3.42 (s, 3H), 3.91 (s, 3H), 4.67 (s, 2H), 5.09 (s, 1H), 5.44 (s, 1H), 6.91 (d, J = 8.8 Hz, 2H), 6.96 (t, J = 7.4 Hz, 1H), 7.30 (m, 4H), 7.98 (d, J = 8.8 Hz, 2H); ^{13}C NMR ($CDCl_3$) 37.8, 52.5, 68.7, 114.9, 121.4, 121.9, 126.6, 128.7, 129.7, 130.9, 140.0, 148.7, 158.5, 166.5, 169.3. Anal. Calcd for $C_{19}H_{19}NO_4$: C, 70.14%; H, 5.89%; N, 4.30%. Found: C, 69.96%; H, 5.85%; N, 4.37%.

Preparation of Methyl 1-Methyl-2-oxo-3-(phenoxymethyl)-1,2,3,4-tetrahydroquinoline-6-carboxylate (6a, LG$^-$ = PhO$^-$). A solution of 0.23 g (0.71 mmol) of **4a** (LG$^-$ = PhO$^-$) in N_2 saturated 250 mL of benzene containing several crystals of *p*-methoxyphenol as a radical inhibitor was irradiated with a 450 W Hanovia medium pressure mercury lamp in an immersion well apparatus for 8 h with stirring. The solvent was removed in vacuo, and the residue was chromatographed on silica gel, eluting with 10% ethyl acetate in hexane, to give 0.16 g (0.49 mmol, 69% yield) of **6a** (LG$^-$ = PhO$^-$) as a colorless crystals, mp 161−164 °C. The spectral data were as follows: ^{1}H NMR ($CDCl_3$) δ 3.01−3.06 (m, 2H), 3.24 (dd, J = 9.96, 21.3 Hz, 1H), 3.42 (s, 3H), 3.91 (s, 3H), 4.19 (dd, J = 2.94, 9.42 Hz, 1H), 4.49 (dd, J = 2.94, 9.42 Hz, 1H), 6.92−7.05 (m, 3H), 7.29 (t, J = 7.47 Hz, 2H), 7.92 (s, 1H), 7.98 (dd, J = 1.92, 8.46 Hz, 1H); ^{13}C NMR ($CDCl_3$) 28.7, 30.2, 40.7, 52.3, 66.8, 114.6, 114.8, 121.3, 124.9, 125.3, 129.7, 129.8, 129.9, 144.2, 158.8, 166.8, 170.2.

Preparation of Methyl 4-[{2-[(Bocalanyloxy)methyl]acryloyl}-(methyl)amino]benzoate (4a, LG$^-$ = BocAla). To a solution of 1.0 g (4.0 mmol) of **4a** (LG$^-$ = HO$^-$), 0.76 g (4.0 mmol) BocAla, and a tiny bit of DMAP in 20 mL of CH_2Cl_2 was added 0.83 g (4.0 mmol) of DCC at room temperature. The reaction mixture was stirred at room temperature for 24 h and concentrated in vacuo. Ether was added, the mixture was filtered, and the filtrate was concentrated in vacuo. The residue was chromatographed on silica gel eluting with 20% of ethyl acetate in hexane, to give 1.32 g (3.1 mmol, yield 78%) of **4a** (LG$^-$ = BocAla) as colorless needles, mp 95−96 °C. The spectral data were as follows: ^{1}H NMR (CD_3CN) δ 1.31 (d, J = 7.32 Hz, 3H), 1.37 (s, 9H), 3.32 (s, 3H), 3.85 (s, 3H), 4.19 (br, 1H), 4.68 (s, 2H), 5.08 (s, 1H), 5.36 (s, 1H), 5.71−5.74 (br, 1H), 7.36 (d, J = 8.82 Hz, 2H), 7.98 (d, J = 8.82 Hz, 2H); ^{13}C NMR ($CDCl_3$) 17.8, 28.4, 37.8, 50.2, 52.7, 65.6, 79.8, 122.4, 127.6, 129.2, 131.2, 140.1, 149.5, 156.3, 166.9, 169.0, 173.6. Anal. Calcd for $C_{21}H_{28}N_2O_7$: C, 59.99%; H, 6.71%; N, 6.66%. Found: C, 60.18%; H, 6.68%; N, 6.79%.

Preparation of Methyl 3-[(Bocalanyloxy)methyl]-1-methyl-2-oxo-1,2,3,4-tetrahydroquinoline-6-carboxylate (6a, LG$^-$ = BocAla). To a solution of 0.19 g (0.78 mmol) of **6a** (LG$^-$ = HO$^-$), 0.16 g (0.82 mmol) of BocAla, and a bit of DMAP in 20 mL of CH_2Cl_2 was added 0.19 g (0.94 mmol) of DCC at room temperature. The reaction mixture was stirred at room temperature for 24 h and concentrated in vacuo. Ether was added, the mixture was filtered, and the filtrate was concentrated in vacuo. The residue was chromatographed on silica gel, eluting with 20% of ethyl acetate in hexane, to give 0.26 g (0.62 mmol, yield 79%) of **6a** (LG$^-$ = BocAla) as colorless needles, mp 110−115 °C. The spectral data were as follows: ^{1}H NMR ($CDCl_3$) δ 1.31 (d, J = 7.2 Hz, 3H), 1.41 (s, 9H), 2.90−3.11 (m, 3H), 3.34 (s, 3H), 3.86 (s, 3H), 4.13 (t, J = 7.0 Hz, 1H), 4.31−4.52 (m, 2H), 5.66 (br, s, 1H), 7.13 (d, J = 8.5 Hz, 1H), 7.84 (s, 1H), 7.92 (dd, J = 1.9, 8.5 Hz, 1H); ^{13}C NMR ($CDCl_3$) δ 1.31 (d, J = 7.32 Hz, 3H), 1.37 (s, 9H), 3.32 (s, 3H), 3.85 (s, 3H), 4.19 (br, 1H), 4.68 (s, 2H), 5.08 (s, 1H), 5.36 (s, 1H), 5.71−5.74 (br, 1H), 7.36 (d, J = 8.82 Hz, 2H), 7.98 (d, J = 8.82 Hz, 2H); ^{13}C NMR ($CDCl_3$) 17.7, 28.4, 30.1, 40.3, 40.4, 50.3,

52.4, 64.1, 79.7, 115.5, 125.1, 126.1, 129.6, 129.9, 145.1, 156.3, 167.1, 170.1, 174.0. Anal. Calcd for $C_{21}H_{28}N_2O_7$: C, 59.99%; H, 6.71%; N, 6.66%. Found: C, 60.26%; H, 6.81%; N, 6.91%.

Preparation of *N*-(4-Benzoylphenyl)-2-(hydroxymethyl)-*N*-methylacrylamide (4b, $LG^- = HO^-$). The procedure was adapted from the literature.[16] To a mixture of 33 g (0.12 mol) of *N*-(4-benzoylphenyl)-*N*-methyl-2-propenamide **11b** in 330 mL of THF were added 330 mL of a 40% aqueous formaldehyde and 33 g (0.29 mol) of DABCO. The suspension was sonicated for 48 h at 50−60 °C. The mixture was extracted with ethyl acetate. The extracts were washed with a saturated solution of $NaHCO_3$, brine, and dried over anhydrous sodium sulfate. After concentration in vacuo, the residue was chromatographed on silica gel, eluting with 20% ethyl acetate in hexane, to give 16 g (0.054 mol, 45% yield) of **4b** ($LG^- = HO^-$) as a yellow solid, mp 90−91 °C. The spectral data were as follows: ^{1}H NMR ($CDCl_3$) δ 2.51 (br, 1H), 3.43 (s, 3H), 4.28 (s, 2H), 5.01 (s, 1H), 5.36 (s, 1H), 7.33 (d, J = 8.7 Hz, 2H), 7.49 (t, J = 7.8 Hz, 2H), 7.61 (t, J = 7.8 Hz, 1H), 7.79 (t, J = 8.7 Hz, 4H); ^{13}C NMR ($CDCl_3$) 37.8, 64.2, 120.4, 126.3, 128.6, 130.1, 131.4, 132.8, 135.8, 137.4, 143.3, 148.2, 170.5, 195.7. Anal. Calcd for $C_{18}H_{17}NO_3$: C, 73.20%; H, 5.80%; N, 4.74%. Found: C, 73.33%; H, 5.85%; N, 4.77%.

Preparation 6-Benzoyl-3-(hydroxymethyl)-1-methyl-3,4-dihydroquinolin-2(1*H*)-one of 6b ($LG^- = HO^-$) by Photolysis of (4b, $LG^- = HO^-$). A solution of 0.38 g (1.3 mmol) of **4b** ($LG^- = HO^-$) in N_2 saturated 250 mL of benzene containing several crystals of *p*-methoxyphenol as a radical inhibitor was irradiated with a 450 W Hanovia medium pressure mercury lamp in an immersion well apparatus with a Pyrex filter for 2 h with stirring. The solvent was removed in vacuo, and the residue was chromatographed on silica gel, eluting with 20% ethyl acetate in hexane, to obtain 0.35 g (1.2 mmol 92% yield) of **6b** ($LG^- = HO^-$) as colorless crystals, mp 111−113 °C. The spectral data were as follows: ^{1}H NMR ($CDCl_3$) δ 2.68−2.91 (m, 3H), 3.37 (s, 3H), 3.87 (t, J = 8.5 Hz, 2H), 7.01 (d, J = 8.3 Hz, 1H), 7.44 (m, 2H), 7.55 (t, J = 7.4 Hz, 1H), 7.70 (m, 4H); ^{13}C NMR ($CDCl_3$) 27.9, 29.9, 42.2, 62.6, 114.3, 125.6, 128.4, 129.9, 129.9, 130.5, 132.2, 132.4, 137.8, 143.5, 172.5, 195.5. Anal. Calcd for $C_{18}H_{17}NO_3$: C, 73.20%; H, 5.80%; N, 4.74%. Found: C, 73.07%; H, 5.79%; N, 4.77%.

Preparation of *N*-(4-Benzoylphenyl)-*N*-methyl-2-[(phenylacetyl)oxy]methylacrylamide (4b, $LG^- = PhCH_2COO^-$). To a solution of 2.8 g (9.5 mmol) of **4b** ($LG^- = HO^-$) and 1.3 mL of triethylamine in 20 mL of CH_2Cl_2 at 0 °C was added, dropwise with stirring, 1.5 g (9.5 mmol) of phenylacetyl chloride in 10 mL of CH_2Cl_2. The reaction was stirred overnight at room temperature. The reaction mixture was washed with 5% $NaHCO_3$ and brine. After drying over anhydrous $MgSO_4$, the solvent was removed in vacuo, and the residue was chromatographed on silica gel, eluting with 10% ethyl acetate in hexane to obtain 2.9 g (7.0 mmol, 74% yield) of NMR pure **4b** ($LG^- = PhCH_2COO^-$) as a colorless oil. The spectral data were as follows: ^{1}H NMR ($CDCl_3$) δ 3.37 (s, 3H), 3.67 (s, 2H), 4.73 (s, 2H), 5.09 (s, 1H), 5.33 (s, 1H), 7.08 (d, J = 8.4 Hz, 2H), 7.26 (m, 2H), 7.28 (m, 4H), 7.51 (d, J = 7.8 Hz, 2H), 7.62 (d, J = 8.1 Hz, 1H), 7.68 (d, J = 8.4 Hz, 2H), 7.77 (d, J = 6.9 Hz, 2H); ^{13}C NMR ($CDCl_3$) 37.9, 41.6, 65.4, 123.1, 126.3, 127.4, 128.6, 128.8, 128.9, 129.5, 130.1, 131.4, 132.8, 135.9, 137.5, 138.9, 148.0, 168.7, 170.9, 195.7. Anal. Calcd for $C_{26}H_{23}NO_4$: C, 75.53%; H, 5.61%; N, 3.39%. Found: C, 75.80%; H, 5.68%; N, 3.49%.

Preparation of 6-Benzoyl-1-methyl-3-[(phenylacetyl)oxymethyl]-3,4-dihydroquinolin-2(1*H*)-one (6b, $LG^- = PhCH_2COO^-$). To a solution of 0.30 g (1.0 mmol) of **6b** ($LG^- = HO^-$) and 0.14 mL of triethylamine in 10 mL of CH_2Cl_2 at 0 °C was added, dropwise with stirring, 0.14 mL (1.1 mmol) of phenylacetyl chloride in 5 mL of CH_2Cl_2. The reaction was stirred overnight at room temperature. The reaction mixture was washed with 5% $NaHCO_3$ and brine. After drying over $MgSO_4$, the solvent was removed in vacuo, and the residue was purified on silica gel, eluting with 10% ethyl acetate in hexane on silica gel to obtain 0.34 g (0.83 mmol, 83% yield) of colorless crystalline product, mp 77−79 °C. The spectral data were as follows: ^{1}H NMR ($CDCl_3$) δ 2.85−2.68 (m, 3H), 3.33 (s, 3H), 3.55 (s, 2H), 4.28 (dd, J = 5.20, 8.40 Hz, 1H), 4.50 (dd, J = 3.33, 8.40 Hz, 1H), 6.96 (d, J = 6.33 Hz, 1H), 7.12−7.24 (m, 5H), 7.43 (t, J = 5.52 Hz, 2H), 7.54 (t, J = 5.56 Hz, 2H), 7.69 (m, 2H); ^{13}C NMR ($CDCl_3$) 28.3, 30.1, 40.0, 41.4, 63.5, 114.4, 124.9, 127.4, 128.6, 128.8, 129.5, 130.0, 130.2, 130.8, 132.3, 132.5, 134.0, 138.0, 143.8, 169.7, 171.6, 195.6. Anal. Calcd for $C_{26}H_{23}NO_4$: C, 75.53%; H, 5.61%; N, 3.39%. Found: C, 75.37%; H, 5.64%; N, 3.38%.

Preparation of *N*-(4-Benzoylphenyl)-*N*-methyl-2-(phenoxymethyl)acrylamide (4b, $LG^- = PhO^-$). The procedure is similar to that reported previously.[17] To a solution of 0.74 g (2.5 mmol) of **4b** ($LG^- = HO^-$), 0.47 g (5.0 mmol) of phenol, and 1.6 g (6.1 mmol) of PPh_3 in 10 mL of dry THF was added 0.95 mL (6.0 mmol) of diethyl azodicarboxylate dropwise at 0 °C under N_2. The reaction mixture was stirred at room temperature for 24 h and concentrated in vacuo, and the residue was chromatographed on silica gel, eluting with 10% ethyl acetate in hexane, to give 0.30 g (0.81 mmol, 32%) of NMR pure **4b** ($LG^- = PhO^-$) as a colorless oil. The spectral data were as follows: ^{1}H NMR ($CDCl_3$) 3.45 (s, 3H), 4.70 (s, 2H), 5.16 (s, 1H), 5.49 (s, 1H), 6.92 (m, 3H), 7.27 (t, J = 8.7 Hz, 2H), 7.31 (d, J = 8.7 Hz, 2H), 7.50 (t, J = 7.6 Hz, 2H), 7.60 (t, J = 7.6 Hz, 1H), 7.78 (d, J = 8.7 Hz, 4H); ^{13}C NMR ($CDCl_3$) 37. 9, 68.7, 114.9, 121.4, 122.0, 126.5, 128.6, 129.7, 130.1, 131.4, 132.8, 135.9, 137.5, 140.0, 148.2, 158.5, 169.3, 195.7. Anal. Calcd for $C_{24}H_{21}NO_3$: C, 77.61%; H, 5.70%; N, 3.77%. Found: C, 77.39%; H, 5.71%; N, 3.82%.

Preparation of 6-Benzoyl-1-methyl-3-(phenoxymethyl)-3,4-dihydroquinolin-2(1*H*)-one (6b, $LG^- = PhO^-$). A solution of 0.10 g (0.27 mmol) of **4b** ($LG^- = PhO^-$) in N_2 saturated 100 mL of benzene containing several crystals of *p*-methoxyphenol as a radical inhibitor in a quartz tube was mounted next to a water-jacketed immersion well apparatus containing a 450 W Hanovia medium pressure mercury lamp and a Pyrex filter. The solution was irradiated for 2 h with stirring. The solvent was removed in vacuo, and the residue was chromatographed on silica gel, eluting with 10% ethyl acetate in hexane, to give 0.067 g (0.18 mmol, 67% yield) of NMR pure **6b** ($LG^- = PhO^-$) as a colorless oil. The spectral data were as follows: ^{1}H NMR ($CDCl_3$) δ 2.99−3.12 (m, 2H), 3.26 (dd, J = 11.6, 21.3 Hz, 1H), 3.44 (s, 3H), 4.19 (dd, J = 7.6, 9.6 Hz, 1H), 4.50 (dd, J = 3.7, 9.6 Hz, 1H), 6.95 (m, 3H), 7.07 (d, J = 8.2 Hz, 1H), 7.29 (t, J = 7.6 Hz, 2H), 7.50 (t, J = 8.0 Hz, 2H), 7.60 (t, J = 7.6 Hz, 1H), 7.75−7.79 (m, 4H); ^{13}C NMR ($CDCl_3$) 28.8, 30.2, 40.6, 66.8, 114.3, 114.8, 121.3, 125.4, 128.5, 129.7, 130.0, 130.3, 130.7, 132.3, 132.5, 138.0, 144.0, 158.8, 170.2, 195.7. Anal. Calcd for $C_{24}H_{21}NO_3$: C, 77.61%; H, 5.70%; N, 3.77%. Found: C, 77.76%; H, 5.59%; N, 3.78%.

Preparation of Methyl 1,3-Dimethyl-2-oxo-1,2,3,4-tetrahydroquinoline-6-carboxylate 3b by Photolysis of 1b. A solution of 1.0 g (4.3 mmol) of **1b** in N_2 saturated 50 mL of benzene containing several crystals of *p*-methoxyphenol as a radical inhibitor in a quartz tube was mounted beside a water-jacketed immersion well apparatus containing a 450 W Hanovia medium pressure mercury lamp. The solution was irradiated for 8 h with stirring. The solvent was removed in vacuo, and the residue was chromatographed on silica gel, eluting with 10% ethyl acetate in hexane, to give 0.6 g (2.6 mmol, 60% yield) of **3b** as colorless crystals, mp 135−137 °C. The spectral data were as follows: ^{1}H NMR ($CDCl_3$) δ 1.26 (d, J = 6.72 Hz, 3H), 2.62−2.71 (m, 1H), 2.73 (dd, J = 11.0, 14.8 Hz, 1H), 3.00 (dd, J = 5.04, 14.8 Hz, 1H), 3.38 (s, 3H), 3.91 (s, 3H), 6.99 (d, J = 8.50 Hz, 1H), 7.84 (s, 1H), 7.94 (d, J = 8.50 Hz, 1H); ^{13}C NMR ($CDCl_3$) 15.8, 30.1, 33.2, 35.5, 52.2, 114.3, 124.4, 125.6, 129.4, 129.6, 144.5, 166.8, 173.4. Anal. Calcd for $C_{13}H_{15}NO_3$: C, 66.94%; H, 6.48%; N, 6.00%. Found: C, 66.72%; H, 6.43%; N, 5.97%.

Preparation of 6-Benzoyl-1,3-dimethyl-3,4-dihydroquinolin-2(1*H*)-one 3c by Photolysis of 1c. A solution of 0.36 g (1.3 mmol) of **1c** in 70 mL of N_2 saturated benzene containing several crystals

of *p*-methoxyphenol as a radical inhibitor in a quartz tube was mounted beside a water-jacketed immersion well apparatus containing a 450 W Hanovia medium pressure mercury lamp and Pyrex filter. The solution was irradiated for 2 h with stirring. The solvent was removed in vacuo, and the residue was crystallized to give 0.36 g (1.3 mmol, 100% yield) of **3c** as colorless crystals, mp 117−119 °C. The spectral data were as follows: ^{1}H NMR ($CDCl_3$) δ 1.27 (d, J = 8.84 Hz, 3H), 2.62−2.79 (m, 2H), 2.99 (dd, J = 6.32, 19.4 Hz, 1H), 3.39 (s, 3H), 7.02 (d, J = 11.08 Hz, 2H), 7.45−7.50 (m, 2H), 7.55−7.60 (m, 1H), 7.69−7.78 (m, 4H); ^{13}C NMR ($CDCl_3$) 15.8, 30.1, 33.2, 35.4, 114.0, 125.7, 128.4, 129.9, 129.9, 130.6, 131.89, 132. 3, 138.0, 144.2, 173.4, 195.6.

Preparation of 5,7-Dimethoxy-1,3-dimethyl-3,4-dihydroquinolin-2(1*H*)-one (9a) by Photolysis of 8a. A solution of 2.0 g (8.5 mmol) of **8a** in N_2 saturated 200 mL of benzene containing several crystals of *p*-methoxyphenol as a radical inhibitor was irradiated with a 450 W Hanovia medium pressure mercury lamp in an immersion well apparatus for 6 h with stirring. The solvent was removed in vacuo, and the residue was chromatographed on silica gel, eluting with 10% ethyl acetate in hexane, to give 1.0 g (4.2 mmol, 50% yield) of **9a**, as colorless crystals, mp 129−130 °C. The spectral data were as follows: ^{1}H NMR ($CDCl_3$) δ 1.24 (d, J = 6.69 Hz, 3H), 2.40−2.60 (m, 2H), 3.00 (dd, J = 5.22, 14.97 Hz, 1H), 3.32 (s, 3H), 3.82 (s, 6H), 6.20 (dd, J = 2.16, 9.60 Hz, 2H); ^{13}C NMR ($CDCl_3$) 16.0, 25.6, 30.3, 35.4, 55.6, 55.8, 92.6, 94.1, 106.3, 142.2, 157.3, 159.8, 173.8. Anal. Calcd for $C_{13}H_{17}NO_3$: C, 66.36%; H, 7.28%; N, 5.95%. Found: C, 66.35%; H, 7.21%; N, 5.96%.

Preparation of 6-Methoxy-1,3-dimethyl-3,4-dihydroquinolin-2(1*H*)-one (9b) by Photolysis of 8b. A solution of 2.6 g (13 mmol) of **8b** in N_2 saturated 250 mL of benzene containing several crystals of *p*-methoxyphenol as a radical inhibitor was irradiated with a 450 W Hanovia medium pressure mercury lamp in an immersion well for 10 h with stirring. The solvent was removed in vacuo, and the residue was chromatographed on silica gel, eluting with 10% ethyl acetate in hexane, to obtain 1.8 g (8.8 mmol, 68% yield) of **9b** as a colorless solid, mp 41−44 °C. The spectral data were as follows: ^{1}H NMR ($CDCl_3$) δ 1.21 (d, J = 6.63 Hz, 3H), 2.53−2.66 (m, 2H), 2.83 (dd, J = 4.20, 13.8 Hz, 1H), 3.29 (s, 3H), 3.75 (s, 3H), 6.68−6.75 (m, 2H), 6.84 (d, J = 8.7 Hz, 1H); ^{13}C NMR ($CDCl_3$) 15.8, 30.0, 33.6, 35.5, 55.6, 111.8, 114.1, 115.4, 127.2, 134.1, 155.3, 172.8.

Preparative Photolysis of Methyl 4-[*N*-Methyl-*N*-(2-phenylacetyloxymethyl-1-oxo-2-propenyl)amino]benzoate (4a, LG^- = $PhCH_2COO^-$). A solution of 0.21 g (0.57 mmol) of **4a** (LG^- = $PhCH_2COO^-$) in N_2 saturated 250 mL of acetonitrile and buffer (1:1) was irradiated with a 450 W Hanovia medium pressure mercury lamp in an immersion well apparatus for 5 h with stirring. The photolysate was concentrated in vacuo and then was extracted by ethyl acetate. The extract was dried over anhydrous sodium sulfate and concentrated in vacuo to obtain an oil, and the oil was chromatographed on silica gel, eluting with 10% ethyl acetate in hexane, to obtain 0.037 g (0.16 mmol, 28% yield) of NMR pure methyl 1-methyl-3-methylene-2-oxo-1,2,3,4-tetrahydroquinoline-6-carboxylate (**5a**) and a mixture of 0.025 g (0.068 mmol, 12% yield) of **6a** (LG^- = $PhCH_2COO^-$) and 0.12 g (0.33 mmol, 57% yield unreacted) of **4a** (LG^- = $PhCH_2COO^-$). The spectral data for **5a** were as follows: ^{1}H NMR ($CDCl_3$) δ 3.48 (s, 3H), 3.78 (s, 2H), 3.91 (s, 3H), 5.53 (s, 1H), 6.19 (s, 1H), 7.01 (d, J = 8.8 Hz, 1H), 7.85 (s, 1H), 7.93 (d, J = 8.8 Hz, 1H); ^{13}C NMR ($CDCl_3$) 30.4, 34.2, 52.3, 114.4, 123.9, 124.2, 124.6, 129.0, 129.6, 135.3, 143. 8, 165.2, 166.7.

Preparative Photolysis of *N*-(4-Benzoylphenyl)-*N*-methyl-2-phenylacetyloxymethyl-2-propenamide (4b, LG^- = $PhCH_2COO^-$). A solution of 0.29 g (0.70 mmol) of **4b** (LG^- = $PhCH_2COO^-$) in N_2 saturated 300 mL of acetonitrile and buffer (1:1) was irradiated with a 450 W Hanovia medium pressure mercury lamp with a Pyrex filter for 2 h with stirring. The photolysate was concentrated in vacuo and then was extracted by ethyl acetate. The extract was dried over anhydrous sodium sulfate and concentrated in vacuo to obtain an oil. The oil was chromatographed on silica gel, eluting with 10% ethyl acetate in hexane, to obtain 0.044 g (0.16 mmol, 23% yield) of NMR pure 6-benzoyl-1-methyl-3-methylene-3,4-dihydroquinolin-2(1*H*)-one (**5b**) and a mixture of 0.021 g (0.068 mmol, 11% yield) of **6b** (LG^- = $PhCH_2COO^-$) and 0.12 g (0.29 mmol, 41% yield unreacted) of **4b** (LG^- = $PhCH_2COO^-$). The spectral data for **5b** were as follows: ^{1}H NMR ($CDCl_3$) δ 3.44 (s, 3H), 3.78 (s, 2H), 5.53 (s, 1H), 6.19 (s, 1H), 7.03 (d, J = 8.4 Hz, 1H), 7.48 (t, J = 7.8 Hz, 2H), 7.58 (t, J = 8.0 Hz 1H), 7.68−7.76 (m, 4H); ^{13}C NMR ($CDCl_3$) 30.3, 34.2, 114.1, 124.0, 124.3, 128.5, 129.5, 129.9, 130.6, 132.0, 132.4, 135.2, 137.9, 143.5, 165.1, 195.6.

General Procedure for Determining Product Yields in Photolyses of 4a (LG^- = BocAla, $PhCO_2^-$, $PhCH_2CO_2^-$, PhO^-, HO^-) and 4b (LG^- = $PhCH_2CO_2^-$, PhO^-, HO^-). Samples of 15−20 mg of **4a** (LG^- = $PhCH_2CO_2^-$, PhO^-, HO^-) or **4b** (LG^- = $PhCH_2CO_2^-$, PhO^-, HO^-) in 1 mL of 50% aq CD_3CN containing 0.1 M phosphate buffer at pD 7 or 0.5 mL of CD_3CN or CD_2Cl_2 or C_6D_6 were contained in NMR tubes. Samples were mounted beside a water-jacketed 450 W medium pressure mercury lamp equipped with a Pyrex filter. The samples were at room temperature throughout the photolyses. Yields were determined by ^{1}H NMR spectroscopy using DMSO as the internal standard.

General Procedure for Testing Hydrolytic Stability of 6a (LG^- = $PhCH_2CO_2^-$, BocAla) and 6b (LG^- = $PhCH_2CO_2^-$) in the Dark. The stabilities of **6a** (LG^- = $PhCH_2CO_2^-$, BocAla) and **6b** (LG^- = $PhCH_2CO_2^-$) were determined by HPLC analyses. Samples of 100−150 mg of **6a** (LG^- = $PhCH_2CO_2^-$, BocAla) or **6b** (LG^- = $PhCH_2CO_2^-$) were dissolved in 15 mL of CH_3CN containing 0.021 M biphenyl as an internal standard and 15 mL of 0.1 M phosphate buffer at pH 7. After various time periods, the ratio between biphenyl and **6a** (LG^- = $PhCH_2CO_2^-$, BocAla) or **6b** (LG^- = $PhCH_2CO_2^-$) was checked by HPLC. In each case, the analyses showed no detectable reaction had occurred at room temperature in the dark for at least one week.

General Procedure for Product Quantum Yield Determinations. A semimicro optical bench was used for quantum yield determinations, similar to the apparatus described by Zimmerman.[27] Light from a 200 W high-pressure mercury lamp was passed through an Oriel monochromator, which was set to 310 or 365 nm wavelengths. The light was collimated through a lens. A fraction of the light was diverted 90° by a beam splitter to a 10 × 3.6 cm side quartz cylindrical cell containing an actinometer. The photolysate was contained in a 10 × 1.8 cm quartz cylindrical cell of 25 mL volume. Behind the photolysate was mounted a quartz cylindrical cell containing 25 mL of actinometer. Light output was monitored by ferrioxalate actinometery[28] using the splitting ratio technique. Products were analyzed by HPLC using biphenyl as an internal standard.

General Procedure for Determining Triplet Yields.[22] Solutions of 0.05 M of **1c**, **15**, or benzophenone and 0.15 M of *trans*-piperylene in either benzene or 20% aq CH_3CN were photolyzed at 365 nm for 2−5 h while performing actinometry, as in the quantum yield determinations. The *trans*- and *cis*-piperylenes were quantified on a 20 ft × 0.25 in column packed with 15% 1,2-bis(cyanoethoxy)ethane on Chromosorb P (45−60 mesh) at 40 °C.

General Procedure for Nanosecond Laser Flash Photolysis. The flash photolysis was performed with an Edinburgh Instruments LP920 system equipped with a Continuum Surelite Nd:YAG laser, which gives 10 ns pulses at 355 nm. The sample concentrations were between 2 and 3 mM to give absorbance of 0.7−0.8. The solvent was 50% aq CH_3CN containing 0.1 M phosphate buffer at pH 7. Samples were flushed initially with argon for 30 min, then

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degassed by three freeze−pump−thaw cycles, and then kept under argon. The compounds used for flash photolysis studies were **1c** and **4b** ($LG^- = PhCH_2CO_2^-$, HO^-). The Stern−Volmer quenching studies used the same techniques but with various amounts of sodium 2-naphthalenesulfonate added as the triplet quencher.

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Supporting Information Available: Synthesis procedures for **1b**,**c**, **8a**,**b**, **11a**,**b**, **13**, *N*-(4-benzoylphenyl)-2-methylacrylamide, and *N*-(3,5-dimethoxyphenyl)-2-methylacrylamide. NMR spectra for **1b**,**c**, **3b**,**c**, **4a** (LG^- = BocAla, $PhCO_2^-$, $PhCH_2CO_2^-$, PhO^-, HO^-), **6a** (BocAla, $PhCO_2^-$, $PhCH_2CO_2^-$, PhO^-, HO^-), **4b** ($PhCH_2CO_2^-$, PhO^-, HO^-), **6b** ($PhCH_2CO_2^-$, PhO^-, HO^-), **5a**,**b**, **11a**,**b**, **13**, *N*-(3,5-dimethoxyphenyl)-2-methylacrylamide, and **8a**,**b**. This material is available free of charge via the Internet at http://pubs.acs.org.

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