

Reactivities of Carboxyalkyl-Substituted 1,4,5,8-Naphthalene Diimides in Aqueous Solution

Bindu Abraham, Sun McMasters, Mellisa A. Mullan, and Lisa A. Kelly*

Contribution from the Department of Chemistry and Biochemistry, University of Maryland, Baltimore County, 1000 Hilltop Circle, Baltimore, Maryland 21250

Received October 7, 2003; E-mail: lkelly@umbc.edu.

Abstract: A series of water-soluble 1,4,5,8-naphthalene diimide derivatives has been prepared and their redox and photophysical properties characterized. From laser flash photolysis studies, the triplet excited state of *N,N*-bis[2-(*N*-pyridinium)ethyl]-1,4,5,8-naphthalene diimide (NDI-pyr) was found to undergo oxidative quenching with the electron donors DABCO, tyrosine, and tryptophan as expected from thermodynamics. Interestingly, the reactivities of naphthalene diimides (NDI) possessing α - and β -carboxylic acid substituents ($R = -CH_2COO^-$, $-C(CH_3)_2COO^-$, and $-CH_2CH_2COO^-$) were strikingly different. In these compounds, the transient produced upon 355 nm excitation did not react with the electron donors. Instead, this transient reacted rapidly ($k > 10^8$ – 10^9 M⁻¹ s⁻¹) with known electron acceptors, benzyl viologen and ferricyanide. The transient spectrum of the carboxyalkyl-substituted naphthalimides observed immediately after the laser pulse was nearly identical to the one-electron-reduced form of 1,4,5,8-naphthalene diimide (produced independently using the bis-pyridinium-substituted naphthalimide). From our studies, we conclude that the transient produced upon nanosecond laser flash photolysis of NDI-(CH₂)_{*n*}COO⁻ is the species produced upon intramolecular electron transfer from the carboxylate moiety to the singlet excited state of NDI. In separate experiments, we verified that the singlet excited state of NDI-pyr does, indeed, react intermolecularly with acetate, alanine, and glycine. The process is further substantiated using thermodynamic driving force calculations. The results offer new prospects of the efficient photochemical production of reactive carbon-centered radicals.

Introduction

The development of chemical systems as structural probes in biological macromolecules, as well as therapeutic agents, has led to the design of novel compounds that have specific activities and interactions with biological systems. To possess the desired reactivity, the compound must interact, specifically and non-covalently, with the target of interest and demonstrate appropriate thermal or photochemical activity with the target. Of the compounds that have been studied, naphthalene-based imide and diimide compounds have been shown to exhibit novel reactivities. The compounds are readily derivatized, through the imide nitrogen, to have a variety of functional groups that “tune” the specific interactions with target molecules.

Thermally, the antitumor potential of naphthalimide chromophores has been documented.^{1–3} Structure–activity relationships, studied by correlating DNA binding and cytotoxic potential, in a series of bisnaphthalimide systems have been reported.⁴ The antitumor activity of dendritic polyamine-imide conjugates has also been studied.⁵

To understand the origin of these effects, the interactions of naphthalimide systems with nucleic acids have been characterized. Naphthalimide systems have been shown to be effective intercalating agents with DNA. For example, *N*-alkylamine-substituted naphthalimides have been found to exhibit selective binding toward –GC– base pair regions.⁶ The DNA binding modes of 1,4,5,8-naphthalene diimide bis-intercalators and poly-intercalating DNA-conjugates have also been studied.^{7,8} Finally, the stabilization of bulged oligonucleotide duplexes⁹ and DNA triplexes¹⁰ by functionalized naphthalene diimides has been demonstrated.

Aside from exhibiting a variety of interactions with nucleic acids, functionalized naphthalene diimide compounds are reactive toward nucleotide bases and peptides. Epoxide-functionalized 1,4,5,8-naphthalimides have been shown to site-

- (1) Brana, M. F.; Sanz, A. M.; Castellano, J. M.; Roldan, M. C.; Roldan, C. *Eur. J. Med. Chem.* **1981**, *16*, 207–212.
- (2) Brana, M. F.; J. M., C.; Perron, D.; Maher, C.; Conlon, D.; Bousquet, P. F.; George, J.; Qian, X.; Robinson, S. P. *J. Med. Chem.* **1997**, *40*, 449–454.
- (3) Brana, M. F.; Castellano, J. M.; Moran, M.; Perez de Vega, M. J.; Perron, D.; Conlon, D.; Bousquet, P. F.; Romerdahl, C. A.; Robinson, S. P. *Anti-Cancer Drug Des.* **1996**, *297*–309.

- (4) Bailly, C.; Carrasco, C.; Joubert, A.; Bal, C.; Watzet, N.; Hildebrand, M.-P.; Lansiaux, A.; Colson, P.; Houssier, C.; Cacho, M.; Ramos, A.; Brana, M. F. *Biochemistry* **2003**, *42*, 4136–4150.
- (5) Brana, M. F.; Dominguez, G.; Saez, B.; Romerdahl, C.; Robinson, S.; Barlozzari, T. *Eur. J. Med. Chem.* **2002**, *37*, 541–551.
- (6) Liu, Z.; Hecker, K.; Rill, R. L. *J. Biomol. Struct. Dyn.* **1996**, *14*, 331–338.
- (7) Guelev, V.; Sorey, S.; Hoffman, D. W.; Iverson, B. L. *J. Am. Chem. Soc.* **2002**, *124*, 2864–2865.
- (8) Lokey, R. S.; Kwok, Y.; Guelev, V.; Pursell, C. J.; Hurley, L. H.; Iverson, B. L. *J. Am. Chem. Soc.* **1997**, *119*, 7202–7210.
- (9) Takenaka, S.; Yokoyama, M.; Kondo, H. *Chem. Commun.* **1997**, 115–116.
- (10) Bevers, S.; Schutte, S.; McLaughlin, L. W. *J. Am. Chem. Soc.* **2000**, *122*, 5905–5915.

selectively alkylate –GG– steps.¹¹ In separate work, known metal-chelating tripeptide (gly-gly-his) groups were covalently attached to either side of naphthalene diimide.¹² Upon chelation of Ni(II), the conjugate exhibited 100 times more cleavage of plasmid DNA than the metal tripeptide alone.

Naphthalene diimides have also been shown to exhibit a variety of photoreactivities toward DNA, including long-range guanine oxidation,¹³ and preferential DNA cleavage at the 5'-side of a –GG– step.¹⁴ The photochemical mechanisms of damage by hydroperoxy-substituted naphthalene diimides have been explored using laser flash photolysis.¹⁵ Toward developing protein probes, the oxidation of the heme protein, horseradish peroxidase, mediated by UV excitation of these hydroperoxy-substituted naphthalimides, has also been demonstrated.¹⁶ From product analysis studies, tryptophan oxidation was observed, along with inhibition of horseradish peroxidase activity. Finally, in our laboratory, we have characterized the kinetics of naphthalene diimide-mediated nucleotide and native DNA oxidation.^{17,18} The yield of redox products was found to strongly depend on the degree of association of the naphthalene diimide with DNA.¹⁸

Recently, we have been investigating the fundamental photophysics of a series of water-soluble naphthalene imide and diimide derivatives. In this series, we have included carboxy-alkyl-substituted naphthalene diimides. At physiological pH, deprotonation of the carboxylic acid moiety renders the compounds negatively charged. The inclusion of these compounds is motivated by the desire to use anionic derivatives that do not associate with DNA and/or negatively charged protein domains. Unexpectedly, we have found that these carboxy-substituted naphthalene diimides exhibit photophysical properties and reactivities quite different from their cationic and neutral counterparts. In this report, results of our photophysical studies of a series of water-soluble naphthalene diimide derivatives are presented. Specifically, the nature of the intermediates produced by laser flash photolysis, as a function of the imide substituent, is discussed. The inter- and intramolecular interactions of naphthalendiimide excited states with electron donors and acceptors are reported and used to identify the transients observed by laser flash photolysis. The study reports on the formation of radical intermediates that are efficiently produced from carboxylic acid derivatives of 1,4,5,8-naphthalene diimides. The results are significant, as they introduce new reactive intermediates that have utility as DNA and protein structural probes.

Experimental Section

Materials. 1,4,5,8-Naphthalene diimide derivatives were synthesized from commercially available naphthalene acid anhydrides and amines. 1,4,5,8-Naphthalenetetracarboxylic anhydride (97%) was obtained from Aldrich and recrystallized from DMF prior to use. β -Alanine (99+%), 2-amino-2-methylpropionic acid, and glycine (99%) were obtained from

Aldrich and used as received. Sodium phosphate, monobasic (ultrapure) was obtained from Baker. Tyrosine (99%) was obtained from Fluka and used as received. Tryptophan (98%) was obtained from Sigma and was used after recrystallization in methanol. 1,4-Diazabicyclo[2.2.2]-octane (DABCO) and benzyl viologen (BV²⁺) were recrystallized two times from methanol prior to use. Potassium ferricyanide and potassium acetate were used as received.

Water was deionized and freshly passed through an Ion-Pure Reverse Osmosis system. The system utilizes a point of use cartridge system, followed by UV irradiation to provide >18 M Ω ultrapure, bacteria-free water. Other solvents, including dimethylformamide (DMF), methanol, and acetonitrile, were purchased from Acros and used as received. The synthesis of *N,N'*-bis[2-(*N*-pyridinium)ethyl]-1,4,5,8-naphthalene diimide (NDI-pyr, **1**) has been previously published.¹⁸

***N,N'*-Bis[2-(ethanoic acid)]-1,4,5,8-naphthalene Diimide (NDI-ala, **2**).** Compound **2** was prepared by heating 5.39 g (20 mmol) of 1,4,5,8-naphthalenetetracarboxylic dianhydride and 5.29 g (60 mmol) of β -alanine in 60 mL of DMF for 3.5 h at 120 °C. The orange-colored crude precipitate was obtained after solvent removal under vacuum. The resultant product was washed with cold methanol and a minimum amount of 5 N NH₄OH to dissolve. After drying, recrystallization from methanol afforded a 15% yield. Purity of the compound was assessed by ¹H NMR and elemental analysis. ¹H NMR (DMSO-*d*₆): 13.20 (d, 2H, –COOH), 8.50 (s, 4H, naph), 3.47 (d, 4H, –CH₂), 2.53 (d, 4H, –CH₂). Anal. Calcd (C₂₀H₁₂N₂O₈·2NH₄⁺): C, 54.05; H, 4.53; N, 12.60. Found: C, 53.86; H, 4.56; N, 12.37. UV max (10 mM pH 7.00 phosphate buffer) 382 nm ($\epsilon = 24\,700 \pm 100\text{ M}^{-1}\text{ cm}^{-1}$).

***N,N'*-Bis[carboxymethyl]-1,4,5,8-naphthalene Diimide (NDI-gly, **3**).** 1,4,5,8-Naphthalic dianhydride (1.02 g, 3.8 mmol) and glycine (0.57 g, 7.6 mmol) were combined and suspended in 50 mL of DMF. The mixture was stirred and heated to 100 °C for 18 h. Removal of DMF was carried out under vacuum using a rotary evaporator. The remaining solid was dissolved in ca. 10 mL of dimethyl sulfoxide (DMSO) (99.5%, Aldrich) and warmed until the solution became clear. The solution was cooled overnight, and crystals were collected and washed with cold methanol. This process was repeated twice more, and the recovered product was recovered in 46% yield after drying in vacuo overnight. ¹H NMR (DMSO-*d*₆): 13.25 (s, 2H, –COOH), 8.75 (s, 4H, naph), 4.80 (s, 4H, –CH₂). Anal. Calcd (C₁₈H₁₀N₂O₈): C, 56.55; H, 2.64; N, 7.33; O, 33.48. Found: C, 56.08; H, 2.76; N, 7.22. UV max (10 mM pH 7.00 phosphate buffer): 382 nm ($\epsilon = 24\,700 \pm 100\text{ M}^{-1}\text{ cm}^{-1}$).

***N,N'*-Bis(2-methyl-1-propionic acid)-1,4,5,8-naphthalene Diimide (NDI-iba, **4**).** 1,4,5,8-Naphthalenetetracarboxylic dianhydride (2.06 g, 7.7 mmol) and 2-aminoisobutyric acid (2.12 g, 20 mmol) were heated in 40 mL of DMF at 40 °C. After the solution turned red, the mixture was heated at 85 °C for 9 h. The reaction mixture was cooled and the solvent removed under vacuum by rotary evaporation. After washing 5 times with ethanol, the compound was obtained in 50% yield. Purity was confirmed by NMR and elemental analysis. ¹H NMR (DMSO-*d*₆): 8.50 (s, 4H, naph), 3.47 (s, 6H, –CH₃), 13.20 (d, 2H, –COOH). Anal. Calcd (C₂₂H₁₈N₂O₈): C, 60.27; H, 4.14; N, 6.39. Found: C, 59.71; H, 4.25; N, 6.25. UV max (10 mM pH 7.00 phosphate buffer): 382 nm ($\epsilon = 22\,370 \pm 70\text{ M}^{-1}\text{ cm}^{-1}$).

General Methods. Ground-state absorption spectra were measured using a JASCO V-570 double-beam spectrophotometer. Fluorescence spectra were measured using a SPEX Fluoromax-2 fluorimeter. Spectra were corrected for the emission wavelength dependence of the fluorimeter. An excitation wavelength of 382 nm was used to excite the NDI samples. Quantum yields were calculated using a solution of quinine bisulfate (in 1 N H₂SO₄) having the same optical density as the NDI solutions. Unless otherwise noted, all measurements were made in 10 mM pH 7.00 phosphate buffer.

Laser flash photolysis was used to characterize the electronically excited triplet states and reactive intermediates. The third harmonic (355 nm) of a Nd:YAG laser (Continuum Surelight II, pulse width ~8 ns) was used for flash excitation. A detailed description of the laser

- (11) Okamoto, A.; Nakamura, T.; Yoshida, K.; Nakatani, K.; Saito, I. *Org. Lett.* **2000**, *2*, 3249–3251.
- (12) Steullet, V.; Dixon, D. W. *Bioorg. Med. Chem. Lett.* **1999**, *9*, 2935–2940.
- (13) Nunez, M. E.; Noyes, K. T.; Gianolio, D. A.; McLaughlin, L. W.; Barton, J. K. *Biochemistry* **2000**, *39*, 6190–6199.
- (14) Matsugo, S.; Kawanishi, S.; Yamamoto, K.; Sugiyama, H.; Matsuura, T.; Saito, I. *Angew. Chem., Int. Ed. Engl.* **1991**, *30*, 1351–1353.
- (15) Aveline, B. A.; Matsugo, S.; Redmond, R. W. *J. Am. Chem. Soc.* **1997**, *119*, 11785–11795.
- (16) Yamamoto, T.; Meaeda, Y.; Matsugo, S.; Kitano, H. *Photochem. Photobiol.* **1997**, *66*, 65–71.
- (17) Rogers, J. E.; Kelly, L. A. *J. Am. Chem. Soc.* **1999**, *121*, 3854–3861.
- (18) Rogers, J. E.; Weiss, S. J.; Kelly, L. A. *J. Am. Chem. Soc.* **2000**, *122*, 427–436.

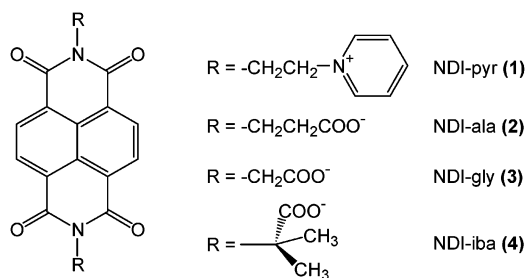


Figure 1. Structures of 1,4,5,8-naphthalene diimide derivatives used in this work.

flash photolysis apparatus has been previously published.¹⁷ Since photodegradation of the naphthalene diimide compounds was observed, photolysis samples were changed after every 15–20 laser shots.

Cyclic voltammetry was used to measure the one- and two-electron reduction potentials of compounds 1–4. All measurements were carried out in a 10 mM (pH 7.0) phosphate buffer. Solutions were bubbled with nitrogen prior to measurement. The cyclic voltammograms were obtained using a BAS Epsilon workstation. Platinum working and counter electrodes were used in conjunction with a Ag/AgCl (ca. 3 M KCl) reference electrode. A scan rate of 50 mV/s was used. Potassium ferricyanide and benzyl viologen were used as standards. The electrochemical half-wave potentials that were measured using the Ag/AgCl reference electrode were converted to a NHE reference. A correction factor was obtained from the difference between the measured reduction potentials of ferricyanide or benzyl viologen and known values vs NHE ($E_{1/2}^{\text{red}}(\text{Fe}(\text{CN})_6^{3-/4-}) = 0.36 \text{ V}^{19}$ and $E_{1/2}^{\text{red}}(\text{BV}^{2+/+}) = -0.37 \text{ V}^{20}$ vs NHE).

Elemental analyses were performed by Atlantic Microlabs, Inc. Proton NMR spectra were measured using a GE QE-300 NMR spectrometer.

Results

Ground-State Characteristics of NDI Derivatives. The structures of the naphthalimide derivatives used in this work are shown in Figure 1. Compound 1 possesses a pyridinium functional group, while compounds 2–4 are ionized and negatively charged at pH 7. The ground-state spectra of these compounds (not shown) exhibit characteristic vibronic peaks in the 300–400 nm region and are nearly identical to those reported for other 1,4,5,8-naphthalimide derivatives.^{15,21–23}

Redox Properties on NDI Derivatives. The redox properties of the NDI derivatives were characterized using cyclic voltammetry. All four compounds reversibly exhibit two one-electron reduction peaks. The reduction potentials are summarized in Table 1. The cationic naphthalimide derivative (1) is more easily reduced than the carboxylic acid derivatives, 2–4. The isobutyric acid derivative 4, where the imide nitrogen is covalently attached to a tertiary carbon, has the most negative reduction potential.

Singlet-State Properties of NDI Derivatives. Naphthalimide derivatives exhibit fluorescence emission spectra in the 360–500 nm region. Spectra recorded in aqueous phosphate buffer are shown in Figure 2. As seen from Figure 2, the fluorescence spectral intensities of the carboxy-substituted NDI

Table 1. Summary of Photophysical and Redox Properties of 1,4,5,8-Naphthalimide Derivatives^a

compound	$\phi_f^{(a)}$	$E_{1/2}(\text{NDI}/\text{NDI}^{\cdot-})$ V vs NHE	$E_{1/2}(\text{NDI}^{\cdot-}/\text{NDI}^{2-})$ V vs NHE
NDI-pyr (1)	0.017 ± 0.001	-0.12 ± 0.03	-0.43 ± 0.03
NDI-ala (2)	0.0009	-0.27 ± 0.05	-0.47 ± 0.05
NDI-gly (3)	0.0009	-0.26 ± 0.04	-0.47 ± 0.04
NDI-iba (4)	0.0004	-0.43 ± 0.02	-0.54 ± 0.02

^a In 10 mM pH 7.00 phosphate buffer using 382 nm excitation and quinine bisulfate in 1 N H₂SO₄ as a standard ($\phi_f = 0.51$).²⁴

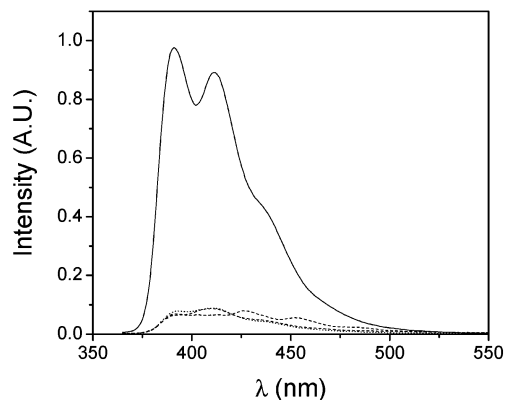


Figure 2. Fluorescence emission spectra of NDI-pyr (solid line) and NDI-ala, NDI-gly, and NDI-iba (dashed lines) measured in 10 mM pH 7.0 phosphate buffer (absorbances of all solutions were matched at the excitation wavelength of 382 nm).

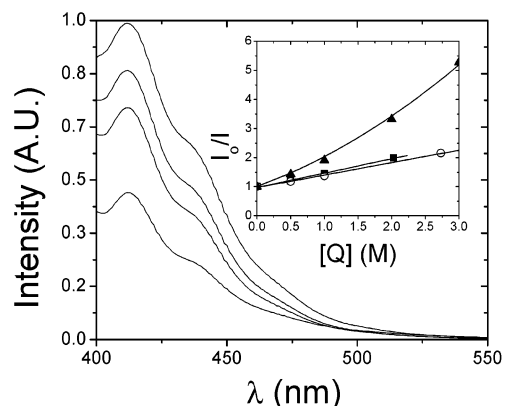


Figure 3. Fluorescence spectrum ($\lambda_{\text{exc}} = 382 \text{ nm}$) of compound 1 containing varying concentrations of glycine (0, 0.5, 1.0, 2.7 M, in order of decreasing intensity). Inset shows the Stern–Volmer quenching plots for acetate (triangles), glycine (circles), and alanine (squares). ([NDI-pyr] = 10 μM in 10 mM pH 7.0 phosphate buffer.)

derivatives 2–4 are substantially lower than that of compound 1. Absolute fluorescence quantum yields were measured and are reported in Table 1. As seen from these values, the quantum yield of NDI-pyr is more than an order of magnitude higher than those of the other compounds. The intrinsic photophysical properties of aromatic imides are generally independent of the functional group (i.e., pyridinium or ethanoic acid side chains). Thus, the result suggests that additional singlet-state deactivation pathways, not present in compound 1, are available in compounds 2–4.

Since compounds 2–4 possess a carboxylic acid functional group, the interactions of the singlet excited state of NDI-pyr with a series of organic acids (glycine, alanine, and acetic acid) were studied. As shown in Figure 3, the fluorescence of NDI-pyr (1) is quenched by acetate, alanine, and glycine.

- (19) Sawyer, D. T.; Sobkowiak, A.; Roberts, J. L. In *Electrochemistry for Chemists*, 2nd ed.; Wiley-Interscience: New York, 1995; p 27.
- (20) Wardman, P. *J. Phys. Chem. Ref. Data* **1989**, *18*, 1637–1723.
- (21) Rodrigues, M. A.; Brochsztain, S.; Barros, T.; Baptisma, M. S.; Politi, M. *J. Photochem. Photobiol.* **1999**, *70*, 35–39.
- (22) Brochsztain, S.; Politi, M. *J. Langmuir* **1999**, *15*, 4486–4494.
- (23) Viehbeck, A.; Goldberg, M. J.; Kovac, C. A. *J. Electrochem. Soc.* **1990**, *137*, 1460–1466.

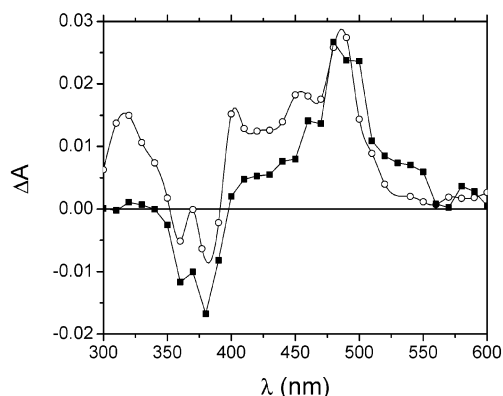


Figure 4. Transient absorption spectra observed immediately after 355 nm excitation of an aqueous solution of NDI-pyr (circles) and NDI-ala (squares) ($[NDI] = 10 \mu\text{M}$ in argon-saturated 10 mM phosphate buffer (pH 7.0)).

By fitting the data according to the Stern–Volmer quenching model (eq 1), Stern–Volmer constants of 0.44 and 0.49 M^{-1} were obtained for glycine and alanine, respectively.

$$\frac{I_o}{I} = 1 + \frac{k_q}{k_d}[Q] \quad (1)$$

In eq 1, I_o and I are the fluorescence intensities in the absence and presence of the quencher (Q), respectively. Using the singlet-state lifetime of NDI-pyr ($280 \text{ ps} = 1/k_d$),¹⁸ bimolecular quenching constants, k_q , of 1.6×10^9 and $1.8 \times 10^9 \text{ M}^{-1} \text{ s}^{-1}$ were obtained for quenching of $^1\text{NDI-pyr}^*$ by glycine and alanine, respectively. In the case of acetate, upward curvature in the Stern–Volmer quenching plot is clearly observed, indicating ground-state association between the positively charged NDI-pyr and acetate ion. By fitting these data to the static quenching model, a Stern–Volmer constant of 0.43 M^{-1} was obtained.²⁵ A rate constant for diffusional quenching by acetate of $1.5 \times 10^9 \text{ M}^{-1} \text{ s}^{-1}$ was calculated. The interpretation and implications of this quenching are discussed below.

Laser Flash Photolysis of NDI Derivatives. Upon excitation with 355 nm light of NDI-pyr, the transient that is immediately formed after the laser pulse has characteristics peaks in the 420 and 480 nm regions (Figure 4). The spectrum is identical to that of the NDI-pyr triplet excited state reported in our earlier work.¹⁸ As seen from Figure 4, the spectrum of NDI-ala is noticeably different than that of NDI-pyr. In particular, the strong absorption bands between 300 and 350 nm observed upon pulsed excitation of **1** are absent in the spectrum of NDI-ala. In addition, the shoulder in the 400–450 nm region is not as pronounced in compound **2** as in **1**. The spectra observed immediately after 355 nm excitation of an aqueous solution of compounds **3** and **4** (not shown) also lack the 300–350 nm absorption band observed for NDI-pyr.

In all four cases, the transient absorption signals decay with first-order kinetics. However, the lifetime of NDI-pyr ($152 \mu\text{s}$) was substantially longer than those observed for compounds **2–4**. The first-order lifetimes of compounds **2**, **3**, and **4** were 63, 57, and $15 \mu\text{s}$, respectively. These lifetimes were measured using $<11 \mu\text{M}$ NDI concentrations. They are very sensitive to

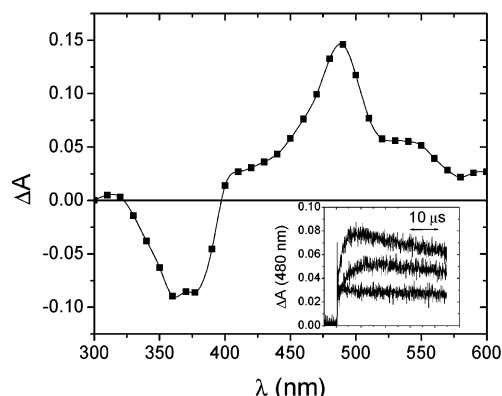
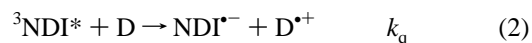


Figure 5. Transient absorption spectrum of **1** ($8 \mu\text{M}$) in pH 7.0 phosphate buffer with 2 mM DABCO ($20 \mu\text{s}$ after 355 nm excitation). Inset shows DABCO concentration-dependent growth of radical anion at 480 nm (0, 1, and 2 mM DABCO). All solutions were argon saturated.

ground-state concentration, and contributions from self-quenching cannot be entirely removed. The concentration range used was within the linear range of the Beer's law plot. Thus, there was no evidence of ground-state aggregation under the conditions used for these experiments.

Triplet-State Reactivity with Electron Donors. The electronically excited states of naphthalene diimide derivatives are known to be reactive toward electron donors, including guanine^{13,17} and DABCO.¹⁵ Charge transfer to the triplet excited state is shown in eq 2.



In earlier work, the spectrum of the one-electron-reduced NDI-pyr, generated following the quenching of the NDI-pyr triplet state with DABCO as an electron donor, was characterized. The NDI-pyr $^{\bullet-}$ radical is characterized by an intense absorption band at 485 nm ($\Delta\epsilon = 83\,000 \text{ M}^{-1} \text{ cm}^{-1}$) and shows no absorption in the 300–350 nm region.¹⁸ As shown in Figure 5, the growth of NDI-pyr $^{\bullet-}$ at 480 nm is clearly observed with increasing concentrations of added DABCO. The transient absorption spectrum of the DABCO-quenching product, shown in Figure 5, is consistent with production of NDI-pyr $^{\bullet-}$.

As expected, the rate of NDI-pyr $^{\bullet-}$ growth is first-order and depends on the concentration of DABCO according to Stern–Volmer kinetics. Similar photophysics were observed when the triplet state of NDI-pyr was quenched by either tryptophan or tyrosine. Specifically, the pseudo-first-order growth of the one-electron-reduced NDI-pyr $^{\bullet-}$ was observed at 480 nm following 355 nm excitation. The bimolecular rate constants for electron transfer from the electron donors to the NDI-pyr triplet excited state are given in Table 2.

By analogy with the reactivity observed upon laser flash photolysis of NDI-pyr with electron donors, we anticipated the other naphthalene diimide derivatives **2–4** to behave analogously. Specifically, we predicted that the transient produced upon 355 nm pulsed excitation of NDI-ala (**2**) would be quenched by DABCO, tryptophan, and tyrosine as electron donors. Surprisingly, no quenching or photoproduct formation was observed at $>\text{mM}$ concentration of these electron donors. Upper limits of the bimolecular rate constants were obtained and are given in Table 2.

Although the one-electron reduction potentials of the anionic naphthalene diimide derivatives are more negative than that of

(24) Demas, J. N. *Excited-State Lifetime Measurements*; Academic Press Inc.: New York, 1983.

(25) Workentin, M. S.; Parker, V. D.; Morkin, T. L.; Wayner, D. D. M. *J. Phys. Chem. A* **1998**, *102*, 6503–6512.

Table 2. Summary of Bimolecular Rate Constants for the Reaction of the Transient Produced upon Pulsed Excitation of Compounds **1** and **2** with Electron Donors or Acceptors (all measurements were obtained in 10 mM pH 7.00 argon-saturated phosphate buffer)

quencher	${}^3\text{NDI-pyr}^*$ (1) k_q ($\text{M}^{-1}\text{s}^{-1}$)	${}^1\text{NDI-ala}$ (2) k_q ($\text{M}^{-1}\text{s}^{-1}$)
DABCO ^a	$(2.5 \pm 0.4) \times 10^8$	$<10^5$
tryptophan ^a	$(6.12 \pm 0.30) \times 10^9$	$<10^5$
tyrosine ^a	$(7.49 \pm 0.26) \times 10^9$	$<10^5$
benzyl viologen ^b	$<10^7$	$(1.30 \pm 0.07) \times 10^9$
$\text{Fe}(\text{CN})_6^{3-}$ ^b	$(1.10 \pm 0.02) \times 10^{10}$	$(3.7 \pm 0.1) \times 10^8$

^a Single-electron donors. ^b Single-electron acceptors.

compound **1** by ca. 100 mV, the redox reaction shown in eq 2 is predicted to be exergonic (vide infra). The one-electron oxidation potentials of the electron donors have been reported: DABCO ($E_{1/2}(\text{DABCO}^{\bullet+}/\text{DABCO}) = 0.56$ V vs NHE),²⁶ tryptophan ($E_{1/2}(\text{trp}^{\bullet+}/\text{trp}) = 1.05$ V vs NHE),²⁷ and tyrosine ($E_{1/2}(\text{tyr}^{\bullet+}/\text{tyr}) = 0.90$ V vs NHE).²⁷ Using these values, along with the reduction potential of NDI-ala (-0.26 V vs NHE) and known triplet excitation energies of naphthalene diimide derivatives (2.03 eV),¹⁷ the free energy change (neglecting solvation) for the electron transfer is estimated to be -1.21 , -0.72 , and -0.87 eV for DABCO, tryptophan, and tyrosine, respectively. In all cases, the energetics are sufficiently downhill that charge transfer to ${}^3\text{NDI-ala}^*$ from the electron donors is expected to occur. Even in the case of compound **4**, which is more difficult to reduce by almost 0.2 eV, the reaction is still predicted to occur on the basis of the thermodynamic calculation.

By virtue of the differences in the transient spectra of **1** and **2** produced upon 355 nm excitation, along with differences in reactivities with electron donors, we propose that the initially formed transients are different in the two cases. The transient absorption spectrum of ${}^3\text{NDI-pyr}^*$ reported herein is identical to those reported for other naphthalene diimide triplet excited states. This species reacts with electron donors as expected on the basis of the thermodynamic driving force calculations. Interestingly, the transient spectrum of NDI-pyr^{•-} shown in Figure 5 strongly resembles the transient produced immediately after 355 nm excitation of compound **2** (Figure 4). The carboxyalkyl-substituted naphthalene diimide derivatives **2–4** do not react with the same electron donors upon 355 nm excitation. Since these results strongly suggest that the species formed upon 355 nm excitation of **1** versus **2** are different, we investigated their reactivity with electron acceptors. We will use the abbreviation ${}^1\text{NDI-ala}$ (and analogous nomenclature for compounds **3** and **4**) for the transient produced upon 355 nm excitation of NDI-ala (**2**) and postulate its identity in the Discussion.

Reactivities of ${}^3\text{NDI-pyr}^*$ and ${}^1\text{NDI-ala}$ with Electron Acceptors. The reactivity of ${}^3\text{NDI-pyr}^*$ with BV^{2+} and $\text{Fe}(\text{CN})_6^{3-}$ was evaluated and compared to that of ${}^1\text{NDI-ala}$. Shown in Figure 6 are the decay traces of ${}^3\text{NDI-pyr}^*$, ${}^1\text{NDI-ala}$, and ${}^1\text{NDI-iba}$ in the absence and presence of BV^{2+} . The decay of the species formed upon 355 nm excitation was monitored at 480 nm, where both the radical anion and triplet excited state have overlapping absorption bands. In addition, production of the one-electron-reduced viologen radical, $\text{BV}^{\bullet+}$,

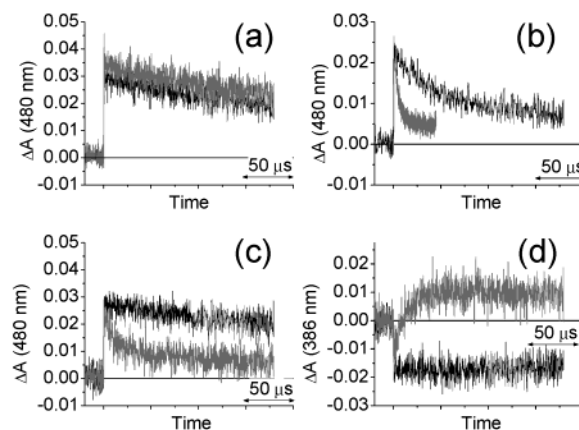


Figure 6. Transient kinetic traces of NDI derivatives with (gray line) and without (black line) benzyl viologen. Panels a, b, and c show traces monitoring at 480 nm for NDI-pyr ($800 \mu\text{M BV}^{2+}$), NDI-ala ($125 \mu\text{M BV}^{2+}$), and NDI-iba ($800 \mu\text{M BV}^{2+}$), respectively. Production of the transient observed at 386 nm for NDI-iba is shown in d. In all cases, the $[\text{NDI}] = 10 \mu\text{M}$ in 10 mM pH 7.0 phosphate buffer (argon saturated).

was monitored at 386 nm.^{28,29} From Figure 6b, it is clear that the transient produced upon 355 nm of NDI-ala (${}^1\text{NDI-ala}$) reacts rapidly with benzyl viologen. Formation of $\text{BV}^{\bullet+}$ as a quenching product was not observed at 386 nm (data not shown). Similar results were observed when NDI-gly was used. Conversely, the triplet decay kinetics of ${}^3\text{NDI-pyr}^*$ were not modified by the addition of benzyl viologen (Figure 6a), indicating that no quenching occurs. In the case of NDI-iba, quenching of the 480 nm transient is observed (Figure 6c), as in the case of NDI-ala. Interesting, the concomitant growth of a quenching product at 386 was noted (Figure 6d).

The reactivities of these species with ferricyanide were also studied. Shown in Figure 7 are the decay traces of ${}^3\text{NDI-pyr}^*$ and ${}^1\text{NDI-ala}$ in the absence and presence of the electron acceptor. As seen from Figure 7, both species are quenched by ferricyanide. By fitting the pseudo-first-order decay constants to the Stern–Volmer kinetic scheme (insets of Figures 7a and 7b), bimolecular rate constants were obtained. These are summarized in Table 2. The transients produced from compounds **3** and **4** were also found to react with ferricyanide (data not shown). The rate constant for the reaction of ${}^1\text{NDI-iba}$ with ferricyanide was found to be $4.8 \times 10^8 \text{ M}^{-1} \text{ s}^{-1}$, very similar to that of ${}^1\text{NDI-ala}$.

The reactivity of one-electron-reduced NDI-pyr ($\text{NDI-pyr}^{\bullet-}$) with $\text{Fe}(\text{CN})_6^{3-}$ was also assessed. The species was produced via triplet-state reaction with DABCO (see above) in the presence of ferricyanide. Concentrations were adjusted so that $>99\%$ of the triplet states were quenched by DABCO to form the NDI radical anion. This DABCO quenching product reacted efficiently with ferricyanide. The bimolecular rate constant for this reaction was found to be by $4.4 \times 10^9 \text{ M}^{-1} \text{ s}^{-1}$ by fitting the concentration-dependent decay to the Stern–Volmer quenching model. The triplet state of NDI-pyr reacted with a slightly higher rate constant than the one-electron-reduced form (see Table 2). This observation is consistent with an enhanced rate of diffusion for reaction of the doubly charged ${}^3\text{NDI-pyr}$ ($2+$) with $\text{Fe}(\text{CN})_6^{3-}$.

Production of Radical Anion of NDI Derivatives. To characterize the spectrum of the one-electron-reduced naphthalene diimide derivatives, the species formed upon reduction of

(26) DeFelippis, M. R.; Murthy, C. P.; Broitman, F.; Weinraub, D.; Faraggi, M.; Klapper, M. H. *J. Phys. Chem.* **1991**, *95*, 3416–3419.

(27) Tsukhara, K.; Wilkins, R. G. *J. Am. Chem. Soc.* **1985**, *107*, 2632–2635.

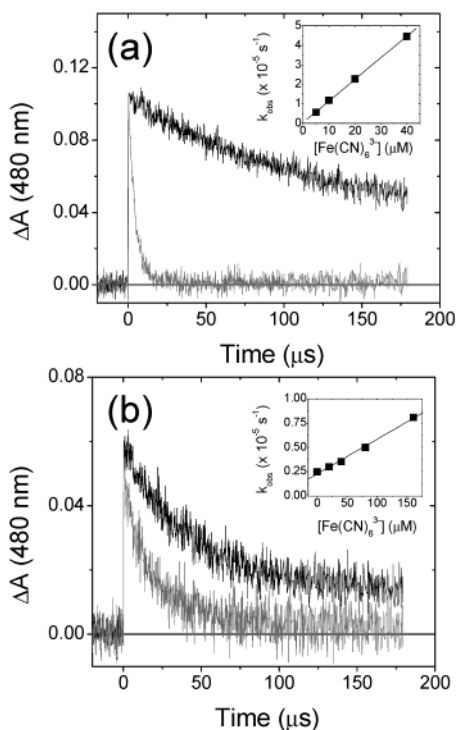
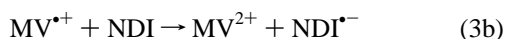
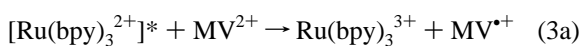


Figure 7. Transient kinetic traces of NDI derivatives with (gray line) and without (black line) $\text{Fe}(\text{CN})_6^{3-}$ (in argon-saturated 10 mM (pH 7.0) phosphate buffer). Panels a and b show traces monitoring at 480 nm for NDI-pyr ($[\text{Fe}(\text{CN})_6^{3-}] = 20 \mu\text{M}$) and NDI-ala ($[\text{Fe}(\text{CN})_6^{3-}] = 80 \mu\text{M}$), respectively ([NDI] = 10 μM). Shown in the insets are Stern–Volmer quenching plots (rate constants given in Table 2).

1–4 was independently generated. Since the transients produced from NDI-ala, NDI-gly, and NDI-iba did not react with DABCO to produce the radical anion, the well-known reaction shown in eq 3a was used to rapidly produce the methyl viologen radical cation as the NDI reducing agent.



The radical cation of methyl viologen was produced via 532 nm excitation of tris(bipyridyl)ruthenium(II) (77 μM) in the presence of a high concentration (9 mM) of methyl viologen. The viologen radical possesses distinct absorbances at 606 and 395 nm ($\Delta\epsilon_{\text{MV}^{\bullet+}}$ = of 13 700 $\text{M}^{-1} \text{cm}^{-1}$ and 42 100 $\text{M}^{-1} \text{cm}^{-1}$ at 606 and 395 nm, respectively).³⁰ As seen in Figure 8, production of the viologen radical in the presence of 300 μM NDI clearly shows the growth of the NDI radical anion at 480 nm, concomitant with decay of the viologen radical at 396 nm. After a sufficiently long time (>4 μs) for the reactions shown in eqs 3a and 3b to proceed, the spectrum was recorded and is shown in Figure 8. Since Ru(III) is produced following the quenching of the tris(bipyridyl)ruthenium(II) excited state by methyl viologen, the contribution from the Ru(III)–Ru(II) transient bleach to the absorption of $\text{NDI}^{\bullet-}$ was measured separately (under conditions where NDI-ala is not present in the solution) and subtracted from the measured spectrum. The

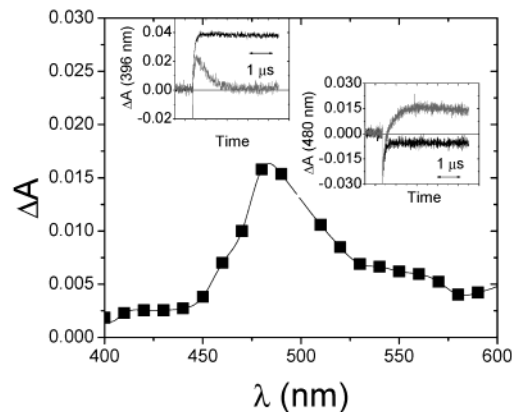


Figure 8. Transient absorption spectrum (4.5 μs after excitation) produced upon 532 nm excitation of an aqueous solution containing 77 μM $\text{Ru}(\text{bpy})_3^{2+}$, 9 mM MV^{2+} , and 300 μM NDI-ala (solution argon saturated). Insets show transient absorption observed without (black line) and with (gray line) 300 μM NDI-ala at the indicated wavelengths.

spectrum shown in Figure 8 bears a strong resemblance to that shown in Figure 4 for $^3\text{NDI-ala}$.

Discussion

In this work, the redox and photophysical properties of a series of water-soluble 1,4,5,8-naphthalene diimide derivatives have been characterized. From the half-wave potentials given in Table 1, the redox properties of the four compounds are quite similar. The small differences that are observed can be qualitatively justified by electrostatic and electronic arguments. Specifically, in the case of the cationic NDI-pyr, it is not surprising that the one-electron-reduced form is somewhat stabilized relative to its anionic counterparts, rendering the reduction potential slightly more positive. Conversely, in the case of NDI-iba, one would expect the inductive effects of the tertiary carbon attached to the imide nitrogen to destabilize the one-electron-reduced form of the compound, rendering the reduction potential slightly more negative. However, in both cases, the differences are small (100–200 mV) and do not significantly impact the exergonicity of the photoinduced redox reactions investigated in this work.

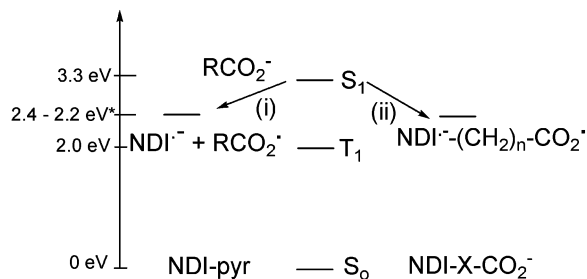
From the fluorescence spectra of the four compounds shown in Figure 2, it is apparent that the singlet states of compounds 2–4 are rapidly quenched by a pathway that is absent in compound 1. In this study, we have demonstrated that, at pH 7, organic acids are efficient quenchers of the singlet excited state of NDI-pyr. For acetate, glycine, and alanine, the bimolecular quenching reaction is diffusion-controlled. At pH 7, the amino groups of glycine and alanine will be predominantly protonated. Thus, we attribute the quenching to electron transfer from the ionized carboxylic acid moiety to the singlet excited state of the naphthalene diimide. In addition, quenching by acetate is clearly observed. The observation that static quenching by acetate occurs, and is absent when glycine or alanine is used as a quencher, is consistent with the net negative charge on the acetate ion (vs the zwitterionic form of glycine or alanine at pH 7). Having demonstrated that intermolecular electron transfer from carboxylate to the singlet excited state of naphthalene diimide does occur, we attribute the low quantum yields measured for compounds 2–4 to the presence of an intramolecular electron transfer pathway (Scheme 1). Using the reduction potential of the naphthalene diimide derivatives reported herein

(28) Farrington, J.; Ebert, M.; Land, E. J. *J. Chem. Soc., Faraday Trans. 1* **1978**, *74*, 665–672.

(29) Watanabe, T.; Honda, K. *J. Phys. Chem.* **1982**, *86*, 2617–2619.

(30) Griesbeck, A. G.; Henz, A.; Kramer, W.; Lex, J.; Nerowski, F.; Oelgemoller, M. *Helv. Chim. Acta* **1997**, *80*, 912–933.

Scheme 1. Energy Diagram for 1,4,5,8-Naphthalimide Excited States and Intermediates Formed Following (i) Inter- and (ii) Intramolecular Photoinduced Electron Transfer (see text and references for details)



* One-electron reduction potential varies among (1) - (4)

(ca. -0.1 to -0.4 V), along with the singlet-state excitation energy measured from the intersection of the absorbance and emission spectrum (3.27 eV), the excited-state reduction potential ($E_{1/2}({}^1\text{NDI}^*/\text{NDI}^{\bullet-})$) is in the range ca. 3.2 – 2.9 V (vs NHE). The oxidation potential of acetate has been reported ($E_{1/2}(\text{OAc}^{\bullet}/\text{OAc}^-) = 2.02$ V vs NHE).²⁶ Thus, we estimate that electron transfer from the organic acids to the singlet excited state of the NDI derivatives is exergonic by ca. 0.9 – 1.1 eV.

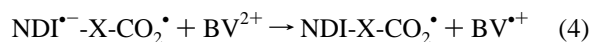
While electron transfer from the organic acids to the singlet excited states of the NDI derivatives is exergonic and occurs (either inter- or intramolecularly) efficiently, the analogous reaction involving the triplet states is thermodynamically uphill (Scheme 1). Experimentally, we did not observe significant quenching of ${}^3\text{NDI-pyr}^*$ even at $>\text{mM}$ concentrations of added acid. A bimolecular rate constant of ca. $10^5 \text{ M}^{-1} \text{ s}^{-1}$ was estimated for this reaction, consistent with the energetics of the process.

The efficiency of this intramolecular electron transfer dictates the nature of the intermediate observed in our laser flash photolysis experiments. While only small differences were observed in the redox properties of the four compounds, the transient spectral features vary substantially with the nature of the imide substituent. From the spectra shown in Figure 4, it is apparent that certain of the features present in the T_1 – T_n spectrum of NDI-pyr are absent in the carboxyalkyl-functionalized compounds. Specifically, the strong absorption bands between 300 and 350 nm in compound **1** are absent in the spectra of compounds **2**–**4**. In addition, the shoulder in 400 – 450 nm region is not as pronounced in these latter compounds as they are in **1**. The spectral features observed upon laser flash excitation of NDI-pyr are identical to those observed for the triplet excited state of this and other 1,4,5,8-naphthalenediimide derivatives.^{15,17,18} In contrast, the transient species observed immediately after pulsed excitation of compounds **2**–**4** bears a strong resemblance to the DABCO quenching product shown in Figure 5. From our laser flash photolysis measurements, we propose that the species formed upon pulsed excitation of compound **1** is the triplet excited state. Conversely, the features observed in the spectrum of compounds **2**–**4** are consistent with the production of $\text{NDI}^{\bullet-}$ from an intramolecular electron transfer to the singlet excited state of the aromatic diimide.

In addition to differences in fluorescence quantum yields and transient spectra, very pronounced differences in triplet-state reactivities were observed. As expected from thermodynamic considerations, electron transfer from the electron donors

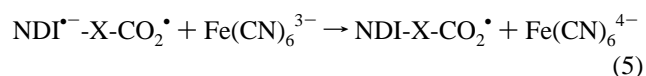
DABCO, tryptophan, and tyrosine to the electronically excited triplet state of the naphthalene diimides should occur with equivalently exergonic driving forces (see above). From the rate constants given in Table 2, it is apparent that all three electron donors do, indeed, quench the triplet excited state of NDI-pyr. In all cases, growth of $\text{NDI}^{\bullet-}$ -pyr is observed as the quenching product (e.g., Figure 5). Conversely, reaction of the transient produced upon flash excitation of compounds **2**–**4** with the same electron donors is more than 4 orders of magnitude slower. This observation is consistent with Scheme 1, since $\text{NDI}^{\bullet-}$ -X- CO_2^{\bullet} possesses no mechanism by which to react with an electron donor. From our electrochemical studies, we expect that electron donors having an oxidation potential ($D^{\bullet+}/D$) more negative than -0.4 to -0.5 V will produce the doubly reduced naphthalene diimide; the potentials for DABCO, tyrosine, and tryptophan are all positive. This reaction is not expected to occur on the basis of thermodynamic considerations.

The one-electron-reduced NDI intermediate ($\text{NDI}^{\bullet-}$ -X- CO_2^{\bullet}) possesses -0.43 to -0.26 eV worth of reducing potential and should react with appropriate electron acceptors. For this reason, we investigated the reactivity of the intermediates with benzyl viologen ($E_{1/2}(\text{BV}^{2+/\bullet+}) = -0.37$ V vs NHE) and ferricyanide ($E_{1/2}(\text{Fe}(\text{CN})_6^{3-/4-}) = 0.36$ V vs NHE). As shown in Figure 6, the ${}^3\text{NDI-pyr}^*$ has very slow reactivity toward BV^{2+} , whereas the transients produced upon pulsed excitation of NDI-ala, NDI-gly, and NDI-iba are efficiently quenched by benzyl viologen at near diffusion-controlled rates (Table 2). Initially, we assigned the quenching reaction in all cases to electron transfer from the intermediate ($\text{NDI}^{\bullet-}$ -X- CO_2^{\bullet}) to benzyl viologen:



If this reaction were occurring, growth of the benzyl viologen radical in the region of 390 nm should be observed. In the case of NDI-iba, this product is, indeed, observed concomitant with the decay of the radical anion absorbing at 480 nm (Figures 6c and 6d). For this compound, reaction 4 is exergonic by ca. 80 mV. For NDI-ala and NDI-gly, the reaction shown in eq 4 is thermodynamically uphill by almost 100 mV. However, in both cases, quenching is still observed. Since quenching products are not observed, the origin of the deactivation of the naphthalimide radical anion in compounds **2** and **3** is unknown. We speculate that the quenching reaction involves hydrogen or proton transfer from the benzylic hydrogens on benzyl viologen. However, further studies are needed to characterize the product.

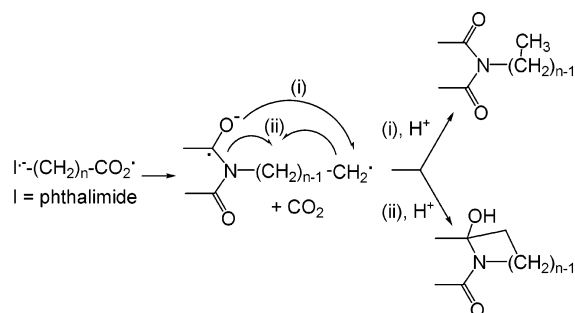
As seen from Figure 7, all of the intermediates react efficiently with ferricyanide as an electron acceptor. In the case of compounds **2**–**4**, we attribute this quenching to one-electron transfer from the reduced NDI intermediate:



In the case of NDI-pyr (compound **1**), triplet-state quenching does not result in long-lived absorbance at 480 nm, where the radical anion is known to absorb. We attribute the quenching either to electron transfer from ${}^3\text{NDI-pyr}^*$ to $\text{Fe}(\text{CN})_6^{3-}$ or to energy transfer to low-lying d–d states.

From our laser flash photolysis studies characterizing the spectral features and reactivities of the laser-induced transients, we conclude that 1,4,5,8-naphthalene diimides possessing a

Scheme 2. Thermal Reactions of Biradical Formed upon Decarboxylation of Carboxyalkyl-Substituted Phthalimides³¹



covalently attached carboxyalkyl substituent rapidly produce $\text{NDI}^{\bullet-}\text{-X-CO}_2^{\bullet}$ via photoinduced intramolecular electron transfer. Support for the feasibility of this reaction is provided by thermodynamic calculations. Interestingly, this identical reaction has been reported for α -amino acid functionalized phthalimides. In a series of papers, Griesbeck et al. have showed that electron-rich carboxylic acid moieties will be oxidized, via intramolecular electron transfer, by electronically excited phthalimides.^{31–34} Following carboxylate oxidation, decarboxylation was found to occur (Scheme 2). From electrochemical and photophysical measurements, the one-electron reduction potential of the phthalimide singlet excited state is estimated to be 3.4 V vs SCE.³⁴ From the results reported herein, we have estimated the analogous potential to be 2.9–3.2 V (vs NHE) for our naphthalimide derivatives. Considering the standard difference between SCE and NHE reference electrode (0.24 eV), the energetics for this reaction are very similar for the two classes of aromatic imides.

In the phthalimide system, decarboxylation of the “charge-separated” intermediate yields a biradical that partitions to give the alkyl-substituted phthalimide or the cyclized product (Scheme 2).³¹ It has been shown that the relative amount of each product depends on solvent and chain length. In separate work, it has been shown that the photochemistry involves the formation of an azomethine ylide.³⁵ Since this decarboxylation reaction should not be dependent on the nature of the aromatic imide, it is likely that the photoinduced electron transfer reaction observed using carboxyalkyl-substituted naphthalene diimides yields reactive, carbon-centered radicals upon UV irradiation.

Preliminary studies were carried out to identify the photo-products formed upon degradation of NDI derivatives formed upon irradiation with light (> 300 nm). The photodegradation of NDI derivatives was monitored by the absorbance spectrum as a function of time. The degraded naphthalimide was isolated and studied using NMR and UV/vis. NMR studies indicate that in the case of NDI-ala, NDI-gly, and NDI-iba, while the naphthalenic hydrogens ($\sim \delta$ 8.75 (s); see Experimental Section)

were undisturbed, the methylenic hydrogens on the side chains had disappeared upon photodegradation and product isolation. MALDI-TOF on the photodegraded product yielded a major product whose molecular weight was 266, corresponding to the parent 1,4,5,8-naphthalene imide. A mechanism consistent with homolytic bond cleavage between imide nitrogen and adjacent carbon, accompanied by protonation of the radical anion, would give rise to formation of 1,4,5,8-naphthalene diimide observed as a photoproduct in the mass and proton NMR spectra. A detailed study elucidating the mechanism will be published separately.

The consequences of this photochemistry are significant: (1) The compounds reported herein are readily prepared and a variety of different spacer groups can be inserted between the naphthalene diimide acceptor and $-\text{CO}_2^-$ donor. (2) Since they can be excited with long-wavelength UV light, where aromatic amino acid and nucleobases do not absorb, the compounds have potential to probe macromolecular structure and interactions in aqueous buffered solutions. (3) Naphthadiimides are already well-known to interact and associate with a variety of biological substrates, including DNA. Although the noncovalent interaction may introduce other deactivation pathways, we expect that a measurable fraction of the singlet excited states will deactivate via the intramolecular electron transfer process reported herein.³⁶ Thus, facile production of very reactive intermediates using predated “biologically reactive” chromophores offers a new class of photoactive DNA and protein structural probes. Experiments are underway to elucidate the nature of the reactivity of this species with biological macromolecules.

Conclusions

In conclusion, we have reported a new mechanism of producing reactive radical intermediates from carboxyalkyl-functionalized 1,4,5,8-naphthalene diimide derivatives. Rapid production of the one-electron-reduced naphthalimide, via intramolecular electron transfer from the covalently attached carboxylate group, is observed following pulsed excitation. Evidence for this reaction pathway is provided by transient spectra, as well as (i) reactivity of the intermediate with electron acceptors and (ii) lack of reactivity with electron donors that are known to react with the triplet state of other naphthalene diimides. We project, by comparison with published work on analogous phthalimide systems, that the photochemistry is followed by rapid homolytic bond cleavage to yield a reactive, carbon-centered radical. The results give rise to a new class of reactive 1,4,5,8-naphthalene diimide compounds that are well-known to have antitumor activity and a variety of DNA/protein interactions.

Acknowledgment. This work was supported by NSF Grant CHE-9984874.

JA0389265

(31) Gorner, H.; Oelgemoller, M.; Griesbeck, A. G. *J. Phys. Chem. A* **2002**, *106*, 1458–1464.

(32) Griesbeck, A. G.; Kramer, W.; Heinrich, T.; Lex, J. *Photochem. Photobiol. Sci.* **2002**, *1*, 237–239.

(33) Griesbeck, A. G.; Schieffer, S. *Photochem. Photobiol. Sci.* **2003**, *2*, 113–117.

(34) Takahashi, Y.; Miyashi, T.; Yoon, U. C.; Oh, S. W.; Mancheno, M.; Su, Z.; Falvey, D.; Mariano, P. S. *J. Am. Chem. Soc.* **1999**, *121*, 3926–3932.

(35) Melhuish, W. H. *J. Phys. Chem.* **1961**, *65*, 229–235.

(36) Using the measured singlet-state lifetime of $^1\text{NDI}^*$ (280 ps, from the pyridinium-substituted compound), along with the quantum yields reported in Table 1, we estimate the rate constants for intramolecular electron transfer from the carboxylate groups in compounds **2–4** to be ca. $(3–11) \times 10^9 \text{ s}^{-1}$.