9b, X = 3-CH_3O: ^1H NMR ($CDCl_3$) δ 8.1-7.9 (m, 1 H), 7.8-7.6 (m, 1 H), 7.5-7.1 (m, 3 H), 7.2 (s, 5 H), 7.0 (d, 1 H, J = 2.0 Hz), 3.9 (s, 3 H), 3.4-3.2 (m, 2 H), 3.0-2.8 (m, 2 H); GC/MS R_t = 16.6 min, m/z 263 (16), 262 (79), 172 (100), 141 (24), 128 (39), 127 (10), 115 (24), 91 (20).

9c, X = 4-CH_3O: ^1H NMR ($CDCl_3$) δ 8.5-8.3 (m, 1 H), 8.1-7.9 (m, 1 H), 7.7-7.7 (m, 3 H), 7.2 (s, 5 H), 6.7 (d, 1 H, J = 8.0 Hz), 3.8 (s, 3 H), 3.4-3.2 (m, 2 H), 3.0-2.8 (m, 2 H); GC/MS R_t = 17.1 min, m/z 263 (3), 262 (17), 172 (11), 171 (100), 128 (28), 127 (13), 115 (6).

9d, X = 4-CH_3. Since this product was formed only in trace amounts, it was not isolated. It was identified by GC/MS: R_t = 16.4 min, m/z 247 (15), 246 (68), 156 (10), 155 (100), 141 (28), 127 (12), 115 (11).

9e, X = 4-CN: ^1H NMR ($CDCl_3$) δ 8.3-8.0 (m, 2 H), 7.8-7.5 (m, 3 H), 7.3 (d, 1 H, J = 7.8 Hz), 7.2 (s, 5 H), 3.5-3.3 (m, 2 H), 3.2-3.0 (m, 2 H); GC/MS R_t = 18.4 min, m/z 258 (6), 257 (30), 166 (23), 140 (8), 91 (100), 65 (10).

9f, X = 4-OCH_2CH_3: ^1H NMR ($CDCl_3$) δ 8.4-8.0 (m, 2 H), 7.7-7.5 (m, 2 H), 7.3-7.1 (m, 6 H), 6.8 (d, J = 7.9 Hz, 1 H), 4.3 (q, J = 7.8 Hz, 2 H), 3.5-3.0 (m, 4 H), 1.6 (t, J = 7.8 Hz, 3 H); GC/MS R_t = 17.8 min, m/z 277 (5), 276 (20), 186 (20), 185 (100), 171 (21), 157 (42), 128 (19).

9j, X = 4-OCH_3, Y = 8-OCH_3: ^1H NMR ($CDCl_3$) δ 8.0 (d, 1 H, J = 8.0 Hz), 7.5 (d, J = 8.0 Hz, 1 H), 7.3 (s, 5 H), 7.2 (t, J = 7.8 Hz, 1 H), 7.0 (d, 1 H, J = 8.0 Hz), 6.8 (d, J = 8.0 Hz, 1 H), 4.0 (s, 3 H), 3.9 (s, 3 H), 3.5-3.2 (m, 2 H), 3.1-2.8 (m, 2 H); GC/MS R_t = 20.1 min, m/z 293 (6), 292 (26), 202 (13), 201 (100), 171 (11), 128 (16), 115 (10).

9i, X = 4-OCH_3, Y = 7-OCH_3: ^1H NMR ($CDCl_3$) δ 8.3 (d, 1 H, J = 8.0 Hz), 7.5-7.1 (m, 8 H), 6.7 (d, J = 8.0 Hz, 1 H), 4.0 (s, 3 H), 3.9 (s, 3 H), 3.3-2.9 (m, 4 H); GC/MS R_t = 20.5 min, m/z 293 (5), 292 (20), 202 (19), 201 (100), 158 (11), 128 (6).

9h, X = 4-OCH_3, Y = 5-OCH_3: ^1H NMR ($CDCl_3$) δ 7.5 (d, J = 8.0 Hz, 1 H), 7.3-7.0 (m, 7 H), 6.9 (d, J = 8.0 Hz, 1 H), 6.7 (d, J = 8.0 Hz, 1 H), 4.0 (s, 3 H), 3.9 (s, 3 H), 3.3-2.9 (m, 4 H); GC/MS R_t = 19.9 min, m/z 293 (3), 292 (19), 202 (13), 201 (100), 157 (5), 128 (10).

9g, X = 4-CO_2CH_3: ^1H NMR ($CDCl_3$) δ 9.1-8.9 (m, 1 H), 8.2-7.9 (m, 2 H), 7.6-7.4 (m, 1 H), 7.3-7.1 (m, 6 H), 4.0 (s, 3 H), 3.6-3.3 (m, 2 H), 3.2-7.9 (9m, 2 H); GC/MS R_t = 20.0 min, m/z 291 (11), 290 (49), 199 (100), 171 (21), 139 (12), 128 (10).

9k, X = 4-F. Since this compound was formed only in trace amounts, isolation was not attempted. It was identified by GC/MS: R_t = 14.3 min, m/z 251 (5), 250 (24), 160 (14), 159 (100), 133 (18), 91 (6).

16c, 9-Methyl-9-(4'-methoxy-1'-naphthylmethyl)fluorene: ^1H NMR ($CDCl_3$) δ 8.4-8.2 (m, 1 H), 7.9-7.0 (m, 12 H), 6.7 (d, 1 H, J = 8.0 Hz), 4.0 (s, 3 H), 3.4 (s, 2 H), 1.5 (s, 3 H); mass spectrum m/z 350 (2), 179 (5), 178 (5), 172 (14), 171 (100), 129 (8).

17, Di-9-methyl-9-fluorene: ^1H NMR ($CDCl_3$) δ 1.6-6.8 (m, 16 H), 1.9 (s, 6 H); mass spectrum m/z 358 (16), 180 (53), 179 (70), 178 (70), 97 (100).

16d, 9-Methyl-9-(4'-methyl-1'-naphthylmethyl)fluorene: ^1H NMR ($CDCl_3$) δ 8.3-6.9 (m, 14 H), 3.5 (s, 2 H), 2.6 (s, 3 H), 1.6 (s, 3 H).

Acknowledgment. We thank NSERC of Canada for financial support. Dr. D. P. DeCosta thanks Dalhousie University for a graduate fellowship. We thank Dr. Samir Farid for helpful discussions and use of software for Marcus theory.

Remote Activation of an Aroyl Azide by Long-Distance Intramolecular Electron Transfer: Irradiation of an Amine-Steroid-Azide System

Yong Zhu and Gary B. Schuster*

Contribution from the Department of Chemistry, Roger Adams Laboratory, University of Illinois, Urbana, Illinois 61801. *Received September 25, 1992*

Abstract: Bichromophoric compounds *cis*- and *trans*-3ξ-(*N*-(*p*-methoxyphenyl)-*N*-methylamino)-5α-androstan-17β-yl 4-(azidocarbonyl)benzoate (**1** and **2**, respectively) were synthesized and studied. Steady-state photophysical measurements indicate that the singlet excited state of the aryl amine (donor) is quenched by the remote aroyl azide (acceptor) group. These findings reveal that it is possible to activate this functional group separated in space from an absorbing "antenna" group. The mechanism of this long-distance interaction is shown by time-resolved spectroscopic measurements and by analysis of the reaction products to be through-bond and, perhaps in one case, through-space electron transfer. The triplet excited state of the donor chromophore also plays a role in the remote activation. It may participate either by long-distance electron or long-distance energy transfer. Intramolecular electron transfer in **1** or **2** generates an aryl amine radical cation and the azide radical anion. The azide radical anion exhibits unique chemical reactions dominated by protonation or by loss of nitrogen to form the nitrene radical anion.

Introduction

Examination of the photochemistry of bichromophoric molecules provides significant insight into factors that control the rate of energy-transfer and electron-transfer reactions. Closs and co-workers employed rigid saturated spacer groups to probe the effect of thermodynamic driving force, distance, solvent, and temperature on rate constants for energy and electron transfer.[1] Their work revealed the Marcus inverted region and provides a theoretical foundation to guide experimentation. Verhoeven, Paddon-Row, and their co-workers controlled the distance from donor to acceptor in rigid compounds and varied systematically donors and acceptors at a single distance.[2] They studied the dependence of the electron-transfer rate on the driving force for reaction and on the distance from donor to acceptor. Their work examined the in-

(1) Miller, J. R.; Calcaterra, L. T.; Closs, G. L. *J. Am. Chem. Soc.* **1984**, *106*, 3047. Closs, G. L.; Miller, J. R. *Science* **1988**, *240*, 440. Closs, G. L.; Piotrowiak, P.; MacInnis, J. M.; Flemming, G. R. *J. Am. Chem. Soc.* **1988**, *110*, 2652. Closs, G. L.; Johnson, M. D.; Miller, J. R. *J. Am. Chem. Soc.* **1989**, *111*, 3751. Liang, N.; Miller, J. R.; Closs, G. L. *J. Am. Chem. Soc.* **1989**, *111*, 8740. Sigman, M. E.; Closs, G. L. *J. Phys. Chem.* **1991**, *95*, 5012.

(2) (a) Oevering, H.; Paddon-Row, M. N.; Heppener, M.; Oliver, A. M.; Cotsaris, E.; Verhoeven, J. W.; Hush, N. S. *J. Am. Chem. Soc.* **1987**, *109*, 3258. (b) Paddon-Row, M. N.; Verhoeven, J. W. *New J. Chem.* **1991**, *15*, 107. (c) Paddon-Row, M. N.; Jordan, K. D. In *Modern Models of Bonding and Delocalization*; Liebman, J. F., Greenberg, A., Eds.; VCH Publications: New York, 1988; Chapter 3. (d) Mes, G. F.; de Jong, B.; van Ramesdonk, H. J.; Verhoeven, J. W.; Warman, J. M.; de Haas, M. P.; Horsman-van der Dod, E. W. *J. Am. Chem. Soc.* **1984**, *106*, 6524. (e) Krijnen, B.; Verhoeven, J. W. *Recl. Trav. Chim. Pays-Bas* **1987**, *106*, 135. (f) Oliver, A. M.; Craig, D. C.; Paddon-Row, M. N.; Kroon, J.; Verhoeven, J. W. *Chem. Phys. Lett.* **1981**, *150*, 366. (g) Oevering, H.; Verhoeven, J. W.; Paddon-Row, M. N.; Warman, J. M. *Tetrahedron* **1989**, *45*, 4751. (h) Clayton, A. H. A.; Ghiggino, K. P.; Wilson, G. J.; Keyte, P. J.; Paddon-Row, M. N. *Chem. Phys. Lett.* **1992**, *195*, 249. (i) Pasman, P.; Rob, F.; Verhoeven, J. W. *J. Am. Chem. Soc.* **1982**, *104*, 5127. (j) Krijnen, B.; Beverloo, H. B.; Verhoeven, J. W.; Reiss, C. A.; Goubitz, K.; Heijdenrijk, D. *J. Am. Chem. Soc.* **1989**, *111*, 4433. (k) Paddon-Row, M. N.; Oliver, A. M.; Warman, J. M.; Smit, K. J.; de Haas, M. P.; Oevering, H.; Verhoeven, J. W. *J. Phys. Chem.* **1988**, *92*, 6958. (l) Jordan, K. D.; Paddon-Row, M. N. *Chem. Rev.* **1992**, *92*, 395.

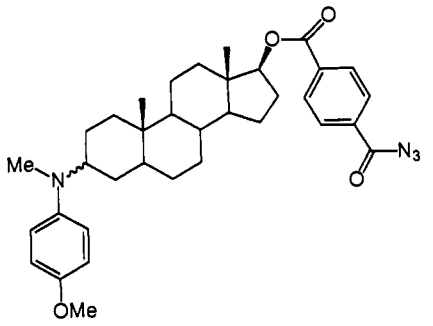
0002-7863/93/1515-2190$04.00/0

terrelation of these factors since the driving force at fixed distance is sensitive to the dielectric constant of the solvent. Recently, Zimmt and Zeng showed significant orbital symmetry dependence for related intramolecular electron-transfer rates.[3] In efforts to model photosynthesis, a series of compounds having a porphyrin linked to a quinone have been prepared, and their intramolecular electron-transfer reactions have been examined. In studies of related reactions with elaborate multiple-part compounds, Gust, Moore, and their co-workers showed that photostimulated separation of charge could be maintained for relatively long times.[4] These and other efforts have resulted in the development of a sophisticated picture of light-driven intramolecular electron-transfer reactions.[5]

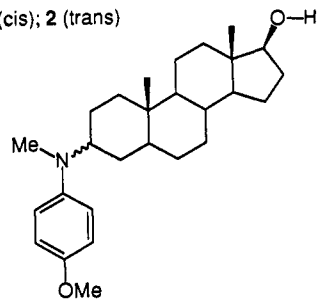
Intramolecular energy transfer has similarly been extensively examined. Keller and Dolby suggested that long-distance triplet energy transfer in rigid bichromophoric systems occurs by a combination of through-bond and through-space mechanisms.[6] Similarly, Zimmerman and co-workers studied the distance dependence of the rate of singlet energy transfer in rigid, rod-shaped compounds.[7] They found that, at short distances, energy transfer occurs by dipole–dipole coupling assisted by transmission through bonds. More recently, Tong and co-workers studied both intramolecular singlet–singlet and triplet–triplet energy transfer between a donor and acceptor separated by a steroidal group.[8] They found that singlet energy transfer occurs by a dipole–dipole mechanism, but that an exchange model fits the results for triplet–triplet energy transfer.

In previous studies of intramolecular electron and energy transfer, the chief objective has been to probe photophysical parameters; irreversible photochemistry, if it occurred, was generally regarded as a nuisance. In contrast, in a preceding report we described the application of through-bond electron transfer leading to the remote activation of an azide.[9] And very recently, Morrison and Wu concluded that long-distance intramolecular triplet energy transfer operating through bonds activates a remote carbonyl group for reaction.[10] We report herein results from a study of the photochemistry of the bichromophoric compounds shown in Chart I. In these systems, the excited singlet state of the aryl amine group is formed directly by light absorption. Long-distance electron or energy transfer activates the aroyl azide group and initiates irreversible chemical reactions. We examined the mode of aroyl azide activation and the mechanism for reaction through radical anion intermediates. The findings reveal that it is possible to activate a reactive functional group separated in space from an absorbing "antenna" group. This finding may have relevance to the use of aroyl azides in related systems[11] as photoaffinity labels for receptors or as photo-cross-linking agents of biological macromolecules since the recognition elements may be separated from the activating groups.

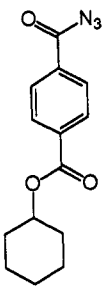
Chart I



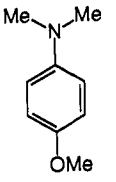
1 (cis); 2 (trans)



3 (cis); 4 (trans)



5



6

Results

(1) Synthesis and Structure of Steroid-Separated Systems 1 and 2. The synthesis of steroid-separated bichromophores **1** and **2** involved two key steps. Reductive amination of 5α-androstan-17β-ol-3-one with *N*-methylanisidine gives isomeric 5α-androstan-17β-ol-3-amines **3** and **4**. After separation, these aryl amine-substituted steroidal alcohols were combined with terephthaloyl chloride and then sodium azide to form **1** and **2**.

The reductive amination of the androstan-3-one gives approximately equal amounts of the diastereomers **3** and **4** in a ratio that depends somewhat on the identity of the reducing agent. This is in contrast to related reductions[12] of this steroid and the reductive amination of cyclohexyl ketones,[13] where one diastereomer often predominates. Fortunately, isomeric alcohols **3** and **4** may be separated by chromatography, analyzed, and independently converted to bichromophoric compounds **1** and **2**.

Structural Analysis of Steroidal Bichromophoric Compounds 1 and 2. The configurations of **1** and **2** can be deduced by NMR spectroscopic analysis of proton–proton coupling constants. The ^{1}H NMR spectrum of the cis isomer shows a broad, relatively downfield peak for the 3-α hydrogen. The 3-β hydrogen of the trans isomer has a narrower, relatively upfield absorption. The chemical shifts of the two epimeric protons at C-3 are unusual compared with the corresponding alcohols or ethers.[12] The α-H absorption of the cis isomer is ca. 0.35 ppm downfield from the β-H of the trans isomer. In addition, the *N*-methyl hydrogen resonance is 0.15 ppm upfield in the cis isomer, and 0.23 ppm

(3) Zeng, Y.; Zimmt, M. B. *J. Am. Chem. Soc.* **1991**, *113*, 5107. Kroon, J.; Oliver, A. M.; Paddon-Row, M. N.; Verhoeven, J. W. *J. Am. Chem. Soc.* **1990**, *112*, 4868.

(4) Gust, D.; Moore, T. A. *Adv. Photochem.* **1991**, *16*, 1. Gust, D.; Moore, T. A. *Top. Curr. Chem.* **1991**, *159*, 103. Gust, D.; Moore, T. A. *Science* **1989**, *244*, 35.

(5) Wasielewski, M. R.; Niemczyk, M. P.; Svec, W. A.; Petit, E. B. *J. Am. Chem. Soc.* **1985**, *107*, 1080. Wasielewski, M. R.; O'Neil, M. P.; Lykke, K. R.; Pellin, M. J.; Gruen, D. M. *J. Am. Chem. Soc.* **1991**, *113*, 2774.

(6) Keller, R. A.; Dolby, L. J. *J. Am. Chem. Soc.* **1967**, *89*, 2768. Keller, K. A. *J. Am. Chem. Soc.* **1968**, *90*, 1940.

(7) Zimmerman, H. E.; McKelvey, R. D. *J. Am. Chem. Soc.* **1971**, *93*, 3638. Zimmerman, H. E.; Goldman, T. D.; Hirzed, T. K.; Schmidt, S. P. *J. Org. Chem.* **1980**, *45*, 3934.

(8) Tong, Z.-H.; Yang, G.-Q.; Wu, S.-K. *Acta Chim. Sin. (Engl. Ed.)* **1989**, 450. Tong, Z.-H.; Yang, G.-Q.; Wu, S.-K. *Chinese J. Chem.* **1990**, 61.

(9) Zhu, Y.; Schuster, G. B. *J. Am. Chem. Soc.* **1990**, *112*, 8583.

(10) Wu, Z.-Z.; Morrison, H. *J. Am. Chem. Soc.* **1992**, *114*, 4119. Wu, Z.-Z.; Nash, J.; Morrison, H. *J. Am. Chem. Soc.* **1992**, *114*, 6640.

(11) Reiser, A.; Wagner, H. M. In *The Chemistry of the Azido Group*; Patai, S., Ed.; Interscience: 1971; p 21. Lwowski, W., In *Azides and Nitrene*, Scriven, E. F. V., Ed.; Academic Press: New York, 1984; p 205. Lwowski, W. In *Nitrene*; Lwowski, W., Ed.; Interscience/John Wiley & Sons, Inc.: New York, 1971; p 185. Autrey, T.; Schuster, G. B. *J. Am. Chem. Soc.* **1987**, *109*, 5814. Sigman, M. E.; Autrey, T.; Schuster, G. B. *J. Am. Chem. Soc.* **1988**, *110*, 4297. Schuster, G. B. In *Photochemical Probes in Biochemistry*; Nielsen, P. E., Ed.; Kluwer Academic: Copenhagen, 1989.

(12) Contreras, R.; Mendoza, L. *Steroids* **1979**, *34*, 2437.

(13) Hutchins, R. O.; Su, W.; Sivakumar, R.; Cistone, F.; Steroho, Y. P. *J. Org. Chem.* **1983**, *48*, 3412.

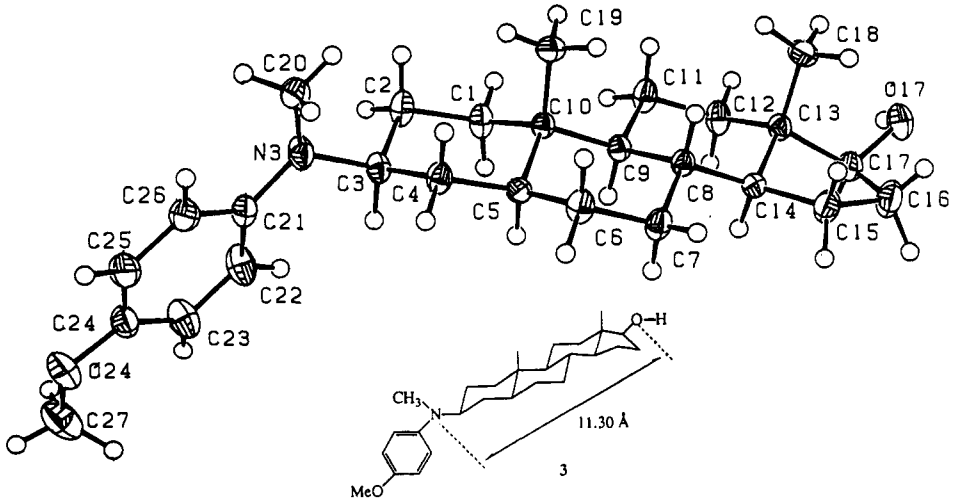


Figure 1. A single crystal of cis aryl amine-substituted steroidal alcohol **3**, analyzed by X-ray crystallography.

further upfield in the trans isomer, compared with that of *p*-methoxy-*N*,*N*-dimethylaniline (**6**).

^{1}H-homonuclear decoupling experiments do not clearly reveal the relevant coupling constants because of overlapping signals. However, analysis of 2D COSY, 2D HECTOR, and ^{13}C APT spectra allows identification of the proton resonances and permits a tentative stereochemical assignment.[14] These experiments are described in the Experimental Section. The stereochemical assignment was confirmed by X-ray crystallography.

A single crystal of the cis aryl amine-substituted steroidal alcohol (**3**), prepared from a hexane/ether/acetone solution, was analyzed by X-ray crystallography. The structure, shown in Figure 1, confirms the assignments made by analysis of the NMR spectra.

Geometries by Molecular Mechanics Calculations. Molecular mechanics calculations were carried out in order to relate the photochemical and photophysical behavior of **1** and **2** to their possible conformations in solution. Application of the PCMODEL (MMX) program[15] allows estimation of the energies of various conformations having different distances and orientations between the aryl amine donor and the azide acceptor groups. The energies of two general conformations, extended and bent, were calculated for each of the isomers. We find that the extended conformation has the lowest energy for the cis isomer. The distances between the donor and acceptor groups in this conformation are much greater than their van der Waals contact distances. The edge-to-edge distance, R_{ee} (defined as the distance between the amine N-21 and ester O-18 atoms), is 11.3 Å, and the center-to-center distance, R_{cc} (between the centers of the donor and acceptor rings), is 17.8 Å in the lowest energy conformation. This calculation is consistent with the data from the crystal structure (R_{ee} = 11.3 Å).

In the cis isomer, the donor and acceptor cannot easily come within the van der Waals contact distance. The molecular mechanics calculations show that the energies of all conformations having the donor and acceptor within contact distance are more than 24 kcal/mol greater than that of the optimized geometry. In contrast, the PCMODEL calculations indicate that the lowest energy conformation of the trans isomer is bent. In this orientation, shown in Figure 2, the distance between the methoxy oxygen atom of the donor group and the terminal nitrogen atom of the acceptor azide (R_{ON}) is 3.2 Å, and R_{cc} is 7.7 Å. Thus, the through-space distance between the aryl amine and aroyl azide groups of **2** is considerably less than it is for **1**.

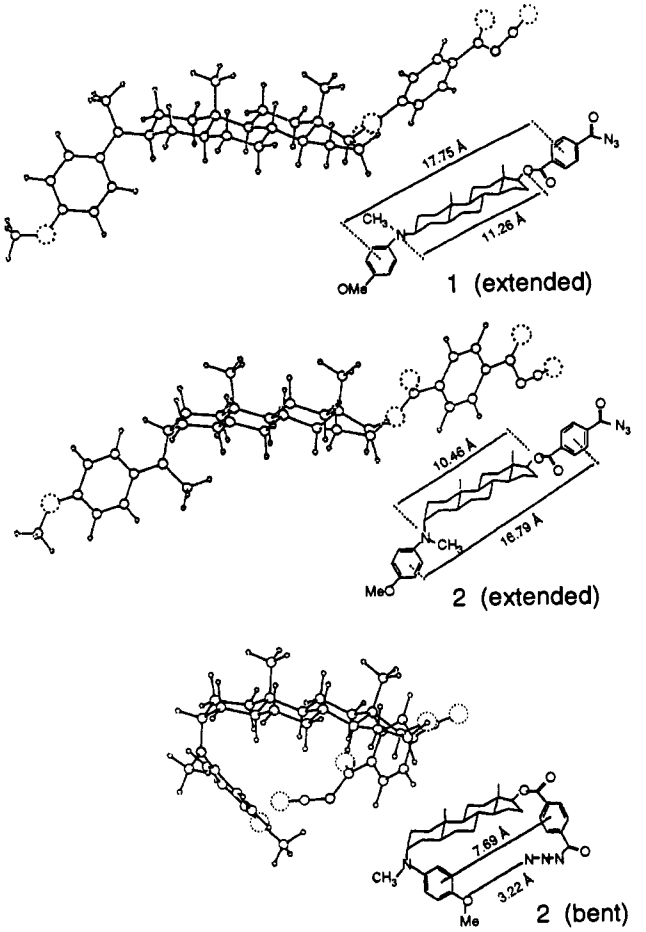


Figure 2. Geometries of cis and trans bichromophoric molecules **1** and **2** optimized by PCMODEL calculations in "bent" and "extended" geometries.

(2) Physical and Spectroscopic Properties. The thermodynamic driving force for photoinduced intramolecular electron and energy transfer from the donor aryl amine group to the acceptor azide group starting from either the singlet or triplet excited states of **1** and **2** was estimated to assess the limits on possible reaction mechanisms. The absorption spectra, emission spectra, fluores-

(14) Bhacca, N. S.; Williams, D. H. *Applications of NMR Spectroscopy in Organic Chemistry*; Holden-Day: San Francisco, 1964. Croasmun, W. R.; Carlson, M. K. In *Two-Dimensional NMR Spectroscopy Applications for Chemists and Biochemists*; Marchand, A. P., Ed.; Methods in Stereochemical Analysis, Vol. 8; VCH: Deerfield, FL, 1992. Gaudemer, A. In *Determination of Configurations by Spectrometric Methods*; Kagan, H. B., Ed.; Thieme: Stuttgart, 1977. Bantia, S.; Pollack, R. M. *J. Am. Chem. Soc.* **1986**, *108*, 3145. Schneider, H. J.; Buchheit, U.; Becker, N.; Schmidt, G.; Siehl, U. *J. Am. Chem. Soc.* **1985**, *107*, 7027.

(15) Molecular geometries and energy minimizations were calculated by using the PCMODEL interactive molecular modeling program (Silicon Graphics workstation; Serena Software, Box 3076, Bloomington, IN 47402-3076). PCMODEL uses the MMX force field including the π-VESCF calculations. The calculations of configuration and conformation were processed with the dielectric constant set at 1.5 D at room temperature. The azide group was modeled as an isocyanate because force constants were not available.

Table I. Spectroscopic and Electrochemical Properties of Chromophores

	absorption[a]		fluorescence[b]					E_{00} (eV)		redox potentials[c]	k_1
compd	λ_{max} (nm)	log ϵ	λ_{ex} (nm)	λ_{em} (nm)	Φ_f	F (%)	τ (ns)	E_{00}^S	E_{00}^T	(V vs Ag)	($\times 10^{-8}$ s^{-1})
					In Cyclohexane						
1	320 (s)	3.37	320	360	0.075	40	1.0				2.6
	254	4.63									
2	320 (s)	2.63	320	360	0.03	72	1.0				11
	253	4.45									
3	320	3.17	320	360	0.12		2.4	3.60			
	254	4.02									
4	320 (s)	2.21	320	360	0.11		2.5	3.60			
	250	3.88									
5	287 (s)	3.34						4.02			
	254	4.31									
6	312	3.37	320	360	0.15		3.0	3.76	2.99[d]		
	248	4.11									
					In CH_3CN						
1	320 (s)	3.27	320	375	0.11	40	3.4				1.5
	255	4.46									
2	320 (s)	2.73	320	375	0.065	60	2.2				2.8
	254	4.34									
3	320	3.26	320	375	0.18		5.5	3.60		0.56	
	255	3.93									
4	320 (s)	2.45	320	375	0.17		5.6	3.60		0.57	
	253	3.70									
5	287 (s)	3.37						4.0		−1.80	
	255	4.18									
6	315	3.43	320	375	0.24		6.5	3.66	3.24[e]	0.62	
	250	4.18									

[a] λ_{max}: Absorption maxima for the ground state. log ϵ: Common logarithm of the extinction coefficient at λ_{max}. [b] λ_{ex}, λ_{em}: Excitation and emission maxima, respectively, of fluorescence at room temperature. Φ_f: Fluorescence quantum yield. F: Fraction of the fluorescence quenched in bichromophoric compound compared with the model chromophore. $F \equiv (\Phi_3 - \Phi_1)/\Phi_3 \times 100\%$, for example. τ: Experimental fluorescence lifetime. [c] The supporting electrolyte is *N*-tetrabutylammonium hexafluorophosphate. The scan rate is 10 000 mV/s. [d] Calculated from phosphorescence, measured in 2-Me-THF at 77 K. [e] Calculated from phosphorescence, measured in EtOH at 77 K.

cence lifetimes, and cyclic voltammetric behavior of the bichromophoric compounds **1** and **2** and the relevant model compounds **3**, **4**, **5**, and **6** were determined. The results of these spectroscopic and electrochemical measurements are listed in Table I. The data show that singlet–singlet energy transfer from the excited aryl amine chromophore to the aroyl azide group is endothermic and, consequently, unlikely. In contrast, electron transfer from either the singlet or triplet excited states of the aryl amine donor to the azide is thermodynamically possible. It is difficult to assess the importance of triplet–triplet energy transfer from the physical and spectroscopic data since the aroyl azide group is not phosphorescent. A more detailed analysis of these data is presented in the Discussion.

The absorption and emission spectra of models for the aryl amine donor (**3** and **4**) and the aroyl azide acceptor (**5**) of **1** and **2** were examined to search for evidence of ground-state interactions between these groups in the bichromophoric compounds.[1,16] The absorption spectra of **1** and **2** are essentially identical with the sum of their chromophoric parts. Significantly, the absorption of the aryl amine group occurs at a longer wavelength than that of the aroyl azide group. This fact permits the selective excitation of the aryl amine moiety in bichromophoric compounds **1** and **2**.

Solvent effects on the absorptions of the model chromophores are insignificant; no meaningful differences are observed in acetonitrile or cyclohexane solution. The fluorescence spectra of bichromophoric compounds **1** and **2** are essentially identical with the spectra of model compounds **3** and **4**. In contrast to the absence of a solvent effect in the absorptions, there is a ca. 15-nm shift to higher energy in the fluorescence emission spectra of the aryl amine-containing chromophores when the solvent is changed from acetonitrile to cyclohexane.

These results, summarized in Table I, indicate that there is no measurable interaction of the aryl amine and aroyl azide chromophores in the ground states of **1** and **2**. Similarly, the fluorescence spectrum of the aryl amine donor is not affected by the aroyl azide group in the bichromophoric compounds. We infer that light absorbed by the aryl amine group in **1** or **2** forms a locally excited state whose properties resemble the isolated chromophore of **3** and **4**.

(3) Fluorescence, Phosphorescence, and Laser Flash Photolysis of Bichromophoric Compounds 1 and 2. Irradiation of bichromophoric compound **1** or **2** at 320 nm generates the lowest energy singlet excited state of the aryl amine chromophore. Since singlet energy transfer to the aroyl azide chromophore is unlikely on thermodynamic grounds, quenching of this state implies operation of the thermodynamically permitted long-distance electron-transfer reaction. We compared the efficiency and dynamics of the fluorescence of **1** and **2** with those of model compounds **3**, **4**, and **6** to assess this possibility.

The fluorescence quantum yield of methoxy aniline **6** in acetonitrile solution is 0.24. The fluorescence efficiencies of the aryl amine-substituted steroids **3** and **4** are essentially the same (but differ from **6**): these data are summarized in Table I. There is a meaningful solvent effect on these fluorescence quantum yields. In cyclohexane solution the fluorescence efficiencies of **3**, **4**, and **6** are lower than they are in acetonitrile solution. We presume that intersystem crossing to form the triplet excited state of the aryl amine group is the most important reaction competing with fluorescence in these model compounds. Laser spectroscopic results, reported later, support this conclusion.

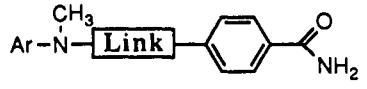
The fluorescence lifetimes of model compounds **3**, **4**, and **6** were determined in acetonitrile and cyclohexane solution. As expected, there are some differences between them. In acetonitrile solution the measured lifetimes (τ) of **3** and **4** are ca. 5.6 ns; in cyclohexane this value is 2.4 ± 1 ns. We measured the fluorescence lifetime of bichromophoric compounds **1** and **2** in both acetonitrile and cyclohexane solution. The lifetime of **1** in the latter solvent is ca. 1 ns, but the lifetime of **2** is too short for us to determine accurately (<1 ns). In acetonitrile solution, singlet lifetimes for **1** and **2** of 3.4 and 2.2 ns, respectively, were obtained. The data are summarized in Table I.

The fluorescence quantum yields of dilute (to avoid bimolecular reactions) solutions of **1** and **2** in both acetonitrile and cyclohexane are significantly lower than for model compounds **3**, **4**, and **6**. The

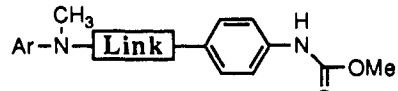
(16) Verhoeven, J. W. *Pure Appl. Chem.* **1986**, *58*, 1285.

Chart II

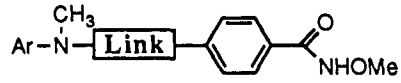
A. Photolysis in Methanol Solution.



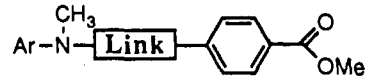
7



8

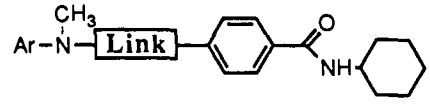


9

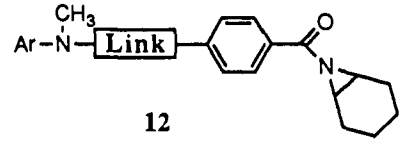


10

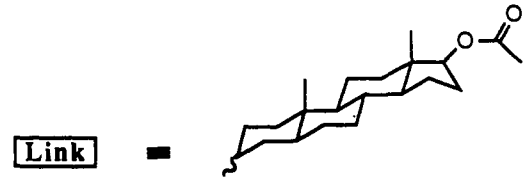
B. Photolysis in Cyclohexane Solution.



11



12



fluorescence efficiencies of **1** and **2** excited at 320 nm are 0.075 and 0.030, respectively; in acetonitrile these values are 0.11 and 0.065. Significantly, under all conditions examined the fluorescence efficiency of the aryl amine group in the bichromophoric compounds is much less than in the model compounds. These findings are consistent with the results of the fluorescence lifetime experiments and indicate that a long-distance quenching reaction operates for **1** and **2** in both acetonitrile and cyclohexane solutions. The rate constant for this quenching reaction (k_1) can be calculated from the excited-state lifetimes and the fluorescence quantum yield for the model aryl amine chromophores compared with those for **1** and **2** according to eq 1. There are some differences between **1** and **2** and between acetonitrile and cyclohexane solution (see Table I), but in all cases $k_1 > 10^8$ s^{-1}.

$$k_1 = (1/\tau)[(\Phi^\circ_f/\Phi_f) - 1] \quad (1)$$

The phosphorescence of methoxyaniline **6** at low temperature in a frozen matrix was studied to estimate the triplet energy of the donor chromophores of **1** and **2**. Both fluorescence and phosphorescence are observed when **6** is irradiated in glassy 2-methyltetrahydrofuran (MTHF) or ethanol at 77 K. The apparent maxima in the phosphorescence emission spectrum occur at 464 and 458 nm in MTHF and ethanol, respectively. Calculation of the triplet energy of **6** requires location of the 0→0 vibronic transition. Unfortunately, the phosphorescence emission does not show distinct vibronic transitions. The 0→0 band location was estimated by normalizing and subtracting the room temperature fluorescence from the low-temperature emission and arbitrarily assigning the 0→0 position at 10% of the maximum phosphorescence intensity. This procedure may introduce a small uncertainty since there may be a shift in the fluorescence spectrum between room temperature and 77 K. On this basis, the triplet energy of **6** is assigned a value of 72 ± 3 kcal/mol; the data are summarized in Table I.

Laser Flash Photolysis of Bichromophoric Compounds 1 and 2. Irradiation of bichromophoric compound **1** in acetonitrile solution at 308 nm (the aryl amine chromophore absorbs) with a 20-ns, 10-mJ pulse from an excimer laser yields the spectrum shown in Figure 3. Similar spectra are obtained when **1** or **2** is irradiated in cyclohexane solution.

The transient spectrum shown in Figure 3 is composed of contributions from at least two species. One species is rapidly quenched by O_2 and, on this basis, is tentatively assigned as a triplet excited state. The other species is much less sensitive to O_2, behavior consistent with its assignment as a radical cation. To confirm the identity of these transients, the triplet–triplet and radical cation absorption spectra of model compound **6** were generated independently.

The triplet and the radical cation of **6** have overlapping spectra. The radical cation of **6** was generated by laser flash photolysis in independent experiments by electron transfer to *trans*-1,2-dicyanoethylene, 9-cyanoanthracene, or anthracene as the electron acceptor. Three different acceptors were used to uncover spectral regions hidden by the triplet–triplet or radical anion absorption spectra of the acceptor.[17] Analysis of these experiments permits assignment of absorption bands at 470 and 490 nm to the radical cation of **6**. The triplet–triplet absorption spectrum of **6** in acetonitrile solution, generated by direct excitation and intersystem crossing, shows maxima at 465, 485, and 520 nm. The triplet state of **6** is quenched rapidly by O_2, and its radical cation is hardly affected by O_2.

The transient spectra recorded after irradiation of bichromophoric compounds **1** and **2** under all conditions examined can be analyzed as a summation of unequal parts of the triplet–triplet and the radical cation absorptions of model chromophore **6**. These findings show convincingly that irradiation of the aryl amine group in **1** or **2** leads to triplet formation and to long-distance electron transfer to the remote aroyl azide group.

(4) Steady-State Photolysis of Bichromophoric Compounds 1 and 2. The photochemistry of **1** and **2** was examined in methyl alcohol, acetonitrile, and cyclohexane solutions in both the presence and the absence of triplet quenchers and nitrene-trapping reagents. The products isolated after irradiation are shown in Chart II without specification of stereochemistry. We presume, however,

(17) Shida, T. *Physical Sciences Data 34: Electronic Absorption Spectra of Radical Ions*; Elsevier: New York, 1988.

Table II. Products from Irradiation of **1** and **2**

substrate	solvent	conversion (%)	quencher	product yields (%)[a] 7	8	9	10[b]	11	12	Me[c]
1	CH_3OH	50		20	0	0	20			
1	CH_3OH	80		58	8	0	4			
1	C_6H_{12}	55		0				45		10
2	C_6H_{12}	30		0				25		5
1	C_6H_{12}	100	C_6H_{10}[d]	0				0	85	<5
1	C_6H_{12}/H_2O	90	C_6H_{10}[d]	10				0	75	20
1	C_6H_{12}/H_2O	95		25				60	0	50
1	CH_3CN	60		35						55
1	CH_3CN	35	O_2[e]	15						25
2	CH_3CN	85		70						30
2	CH_3CN	25	O_2[e]	5						<5
1	CH_3CN (H_2O, 0.2 M)	65	C_6H_{10}[d]	45					0	25

[a] Product yields reported are absolute, i.e., not corrected for conversion. [b] This product is formed by methanolysis during workup of the reaction. [c] Product(s) having lost the *N*-methyl group. [d] Contains 0.2 M cyclohexene. [e] The solution was saturated with O_2 before and during irradiation.

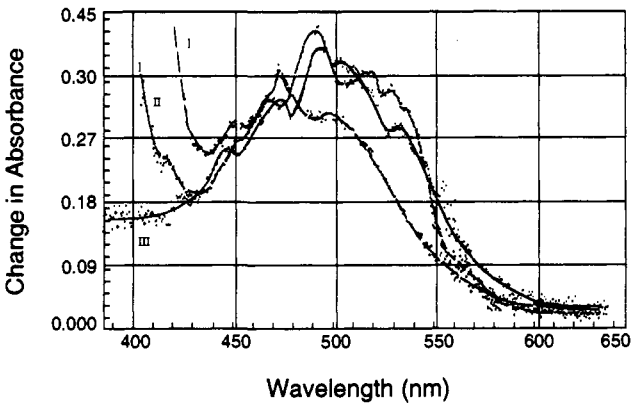


Figure 3. Transient absorption spectra. Curve I is the spectrum of the radical cation of model chromophore **6** generated by irradiation (388 nm) of an O_2-free, anthracene-containing (the electron acceptor) acetonitrile solution. The spectrum was recorded 100 ns after the laser pulse. Curve II is the spectrum of the triplet excited state of model chromophore **6** recorded 100 ns after irradiation of an O_2-free acetonitrile solution at 343 nm. The bands with apparent maxima at 465, 485, and 520 nm are quenched in O_2-containing solutions. The spectrum labeled III was recorded 100 ns after irradiation (308 nm) of an O_2-free acetonitrile solution of **1**. The bands assigned to the triplet are quenched when O_2 is present; the bands assigned to the radical cation are essentially unaffected.

that irradiation of the cis-substituted steroid gives cis-substituted products (similarly for the trans isomer) since isomerization during the photochemical reaction seems unreasonable. NMR spectral analysis of the products supports this assumption.

Irradiation of a N_2-purged methanol solution of **1** (ca. 3×10^{-5} M) at 350 nm (Rayonet Reactor) and −10 °C (to inhibit methanolysis of the azide) gives amide **7** and traces of carbamate **8**. Some of the carbamate may be formed from Curtius rearrangement of the excited singlet state of the aroyl azide formed by stray light absorption, but most of it appears to be formed from unreacted azide during reaction mixture workup. Significantly, we cannot detect any of the hydroxamate (**9**) which is characteristic of reaction of singlet aroyl nitrenes.[11] The data are summarized in Table II. These findings indicate that little or none of the reaction of these azides is initiated by their direct absorption of light. At long irradiation times, when the incident light is absorbed efficiently by the primary products, products that have lost the *N*-methyl group increase in importance. The formation of these products under these conditions may be attributed primarily to secondary photolysis.

Irradiation of **1** or **2** in cyclohexane solution gives the secondary amide **11** formed by insertion of the nitrene into a carbon–hydrogen bond of the solvent. Under these conditions, products from the demethylation of the aryl amine group appear at shorter irradiation times and may be formed both by direct irradiation of the bichromophoric compounds and by secondary photolysis of their photoproducts. When water-saturated cyclohexane solutions are irradiated, small amounts of amide **7** are formed, but formation of **11** is essentially unaffected. Significantly, aziridine **12** is the dominant product when the irradiation of **1** in cyclohexane solution is carried out in the presence of cyclohexene. Aziridination of an olefin is a hallmark reaction of nitrenes.[11,18] This finding demonstrates convincingly that, under these conditions, light absorbed by the aryl amine chromophore leads to loss of N_2 from the remote azide group.

Photolyses of **1** and **2** were also studied in acetonitrile solution. Under these conditions, amide **7**, the major product, is formed by reaction with residual water in the solvent. Addition of additional water, up to 10% volume, does not affect the results. Although there are some differences between the rate constants for quenching of the aryl amine donor group (k_1) in **1** and **2** and between cyclohexane and acetonitrile solutions, the efficiencies of reaction (Φ_{-N_2}) are the same under these conditions within experimental error (±15%). However, irradiation of **1** or **2** in O_2-saturated solutions result in a decrease in Φ_{-N_2}. This observation implicates participation of the triplet excited state of the aryl amine chromophore in the activation of the aroyl azide group. Significantly, in contrast to the results obtained for irradiation of **1** in cyclohexene-containing cyclohexane solution, aziridine **12** is not detected when cyclohexene is present during irradiation of **1** in water-containing acetonitrile or in methanol solutions. Also, saturation of cyclohexene-containing cyclohexane solution with water leads to formation of amide **7** and a decrease in the yield of aziridine **12**. The data are summarized in Table II.

Discussion

The findings reported above show clearly that light absorbed by the aryl amine group of **1** or **2** leads to reaction of the remote aroyl azide group. In this section we consider possible mechanisms for this long-distance activation and discuss the chemistry of the activated aroyl azide group.

(1) Energetic Consideration of Electron-Transfer Reactions. Analysis of the absorption of model donor chromophores **3** and **4** and of acceptor chromophore **5** reveals no overlap of their low-energy tails and shows that singlet–singlet energy transfer from the aryl amine to the aroyl azide is thermodynamically unfavorable by at least 9 kcal/mol. The singlet energy of the aryl amine is 83 kcal/mol in acetonitrile solution and varies only slightly with solvent. The absorption spectrum of the model azide reveals that it has a singlet energy of 92 kcal/mol in acetonitrile. Nevertheless, our experiments show that the singlet excited state of the aryl amine in bichromophoric compounds **1** and **2** is quenched rapidly by the remote aroyl azide group. Since singlet–singlet energy transfer is excluded, we attribute this quenching to long-distance electron transfer.

The effects of solvent and distance on the thermodynamics of long-distance electron transfer have been carefully analyzed by

(18) Reiser, A.; Willets, W.; Terry, G. C.; Williams, V.; Marley, R. *Trans. Faraday Soc.* **1968**, *64*, 3265. Reiser, A.; Marley, R. *Trans. Faraday Soc.* **1968**, *64*, 1806.

Weller[19] and by Verhoeven, Paddon-Row, and their co-workers.[2a] Our evaluation of the energetic considerations for photostimulated intramolecular electron transfer in compounds **1** and **2** closely follows their presentation.

The analysis begins with eq 2, which defines the free energy change for an electron-transfer reaction in the gas phase when the donor and acceptor are at infinite separation ($\Delta G°_\infty$). Under

$$\Delta G°_\infty = IP_D - EA_A - \Delta E_{00} \quad (2)$$

these conditions, the energy of the excited state (ΔE_{00}), the ionization potential of the donor (IP_D), and the electron affinity of the acceptor (EA_A) have clear thermodynamic meaning. Experimentally, it is impossible to obtain values for IP_D and EA_A for compounds such as **1** or **2**, so solution-phase oxidation (E_{ox}) and reduction potentials (E_{red}) are employed. In the best cases, E_{ox} and E_{red} have precise thermodynamic values under the conditions of their determination. Often, however, the oxidation or reduction is irreversible, or these potentials are measured under conditions of solvent, temperature, or electrolyte that are different from the photochemical experiment. In these cases, approximate corrections must be employed to permit calculation of the free energy change for the electron-transfer reaction in solution (ΔG_{et}). Similarly, unlike the ideal case of eq 2, the electron donor and acceptor are not infinitely separated. This gives rise to a Coulombic interaction in the final (ion pair) state that is absent in the initial (neutral) state whose magnitude depends specifically on the distance between the donor and acceptor (R_{cc}) and on the dielectric constant (ϵ) of the medium separating the charges. Methods have been developed to estimate the Coulombic correction to eq 2 that rely on assumption of point charges and that approximate ϵ with the bulk dielectric constant of the medium. Together, the usual approximations lead to eq 3 for estimation

$$\Delta G_{et} = E_{ox}(D) - E_{red}(A) - \Delta E_{00} - [e^2/\epsilon R_{cc}] - [(e^2/r_\pm)(1/37 - 1/\epsilon)] \quad (3)$$

of ΔG_{et} for photostimulated electron transfer between a donor and an acceptor separated by R_{cc} with average individual ionic radii $r_\pm$ in a solvent with dielectric constant ϵ when the redox potentials of the donor and acceptor were determined in acetonitrile solution (ϵ = 37 D).

In estimating ΔG_{et} for bichromophoric compounds **1** and **2**, we set R_{cc} equal to 17.8 Å for the former and 7.7 Å for the latter. These are the values that the PCMODEL calculations predict for the lowest energy conformations.[15] It is likely that other conformations of these systems will be populated within the lifetime of the excited states of the donor. However, analysis of eq 3 shows that at these distances small changes in R_{cc} will have only a minor impact on ΔG_{et}.

The Born correction to the solvation energy requires estimation of the radii of the ionic groups. An average radius, $r_\pm$ = 4.3 Å, was used by assuming that both donor and acceptor are spherical. Cyclic voltammetric measurements of model compounds **3** and **4** show reversible oxidation waves. However, the electrode reactions of model aroyl azide **5** are irreversible. Its reduction potential was estimated from the cathodic peak potential. The data are summarized in Table II.

On the basis of these considerations, the driving force for photostimulated electron transfer originating from singlet excited states of **1** and **2** in their lowest energy conformations are estimated to be −1.38 and −1.40 eV, respectively, in acetonitrile solution. In cyclohexane solution, these values are −0.26 and −0.78 eV. Similarly, the driving force for electron transfer starting from the triplet states of the donor chromophores of **1** and **2** in acetonitrile solution are ca. −0.84 eV. These findings show that long-distance electron-transfer reactions originating from either the singlet or triplet states of **1** and **2** are energetically possible.

(2) Effect of Energetics, Distance, and Solvent on the Dynamics of Electron Transfer. Clearly, the determination of energetic permissibility is not sufficient cause to propose the operation of a reaction mechanism. In order to assess its actual contribution, some estimate of dynamics is required. In recent years, the predictions of Marcus theory[20] for the dynamics of electron-transfer reactions have been verified and refined.[21] In particular, long-distance electron transfer has been observed to occur by both through-bond and through-space (solvent) pathways. In both cases, semiclassical theory provides a guide to the prediction of rate.

In a commonly employed approach,[1] the rate constant for non-adiabatic electron-transfer reactions, k_{et}, is related to ΔG_{et} by the "Golden Rule" formulation of eq 4, where V is a measure of the electronic coupling between states and FCWD is the Franck–Condon weighted density of states. The FCWD factor

$$k_{et} = (4\pi^2/h)V^2(FCWD) \quad (4)$$

contains ΔG_{et} and the internal (λ_i) and solvent (λ_s) reorganization energies. The application of this theory to analysis of k_{et} is clearly reviewed by Gould, Farid, and co-workers.[22] Consideration of the magnitude of V and the effect of λ_s on k_{et} for long-distance electron-transfer reactions has been carefully analyzed by Verhoeven, Paddon-Row, and their co-workers.[2a] Significantly, they find, as have others, that effects of solvent polarity on λ_s are compensated by changes in ΔG_{et} so that k_{et} is almost independent of solvent unless it is thermodynamically unfavorable. Also, recent experiments have confirmed aspects of super-exchange theory that predict a significant magnitude for V through saturated σ-bonded systems.[1,2]

On this basis we conclude that long-distance electron transfer can occur from both excited singlet and triplet states of the donor chromophore of **1** and **2** to the aroyl azide acceptor. This permits attribution of the experimentally determined rate constants, k_1 (Table I), to k_{et}. The rate constant for electron transfer in rigid *donor–spacer–acceptor* systems is often found to depend on the stereochemical relationship of the groups. In the case of **1** and **2**, this dependency is weak, if it is present at all. We attribute this to flexibility in the structures of **1** and **2**. In essence, we measure average k_{et} values over several conformations in solution. Evidently, averaging over conformations smooths the differences normally observed for distinct configurations. Of special note is the observation that k_{et} measured for **2** (where the molecular mechanics calculations predict a close approach of the donor and acceptor groups) in cyclohexane solution is ca. 5 times greater than it is for **1**. This difference may signal operation of a through-space pathway in **2** under these conditions.

We are unable to provide specific evidence for long-distance electron transfer from the triplet state of the donor. However, the observed O_2 dependence of Φ_{-N_2} requires some role for the triplet, and electron transfer cannot be ruled out by consideration of energetic or dynamic factors. Alternatively, activation of the azide by the triplet donor could occur by energy transfer. Since the model azide chromophore exhibits no phosphorescence, we are unable to estimate its triplet energy. And long-distance, through-bond or through-space triplet energy transfer has been invoked previously.[6-8] In analyzing the photochemistry of **1** and **2**, we consider the triplet as, potentially, either an electron donor or an energy donor.

(3) Photochemistry of 1 and 2: Aroyl Azide and Nitrene Radical Anions. The kinetics and spectroscopic data indicate that the initial chemical step after excitation of the donor chromophore of **1** or **2** is electron transfer to form the radical cation of the aryl amine group and the radical anion of the aroyl azide moiety. The chemistry of aryl amine radical cations has been studied exten-

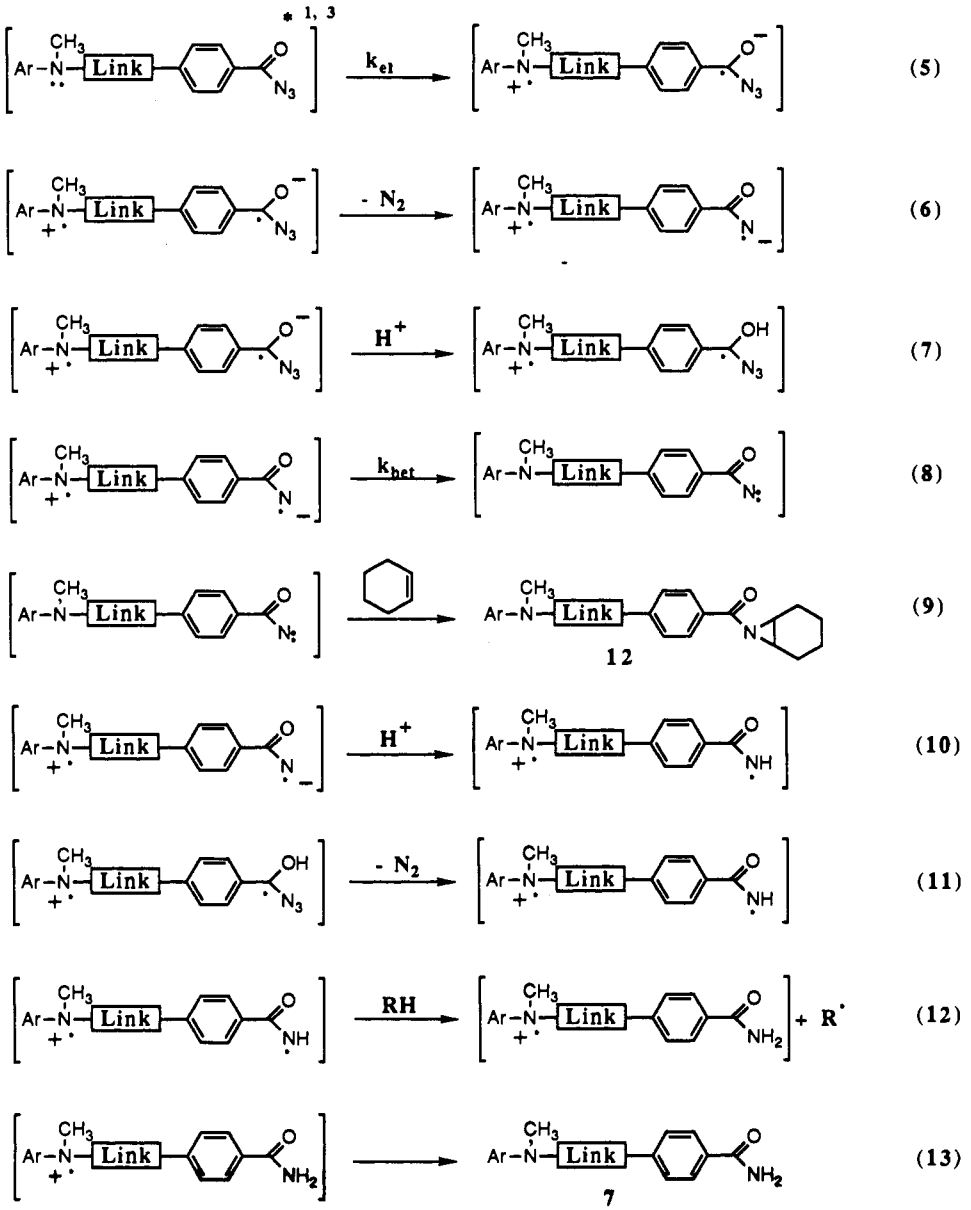
(19) Weller, A. *Z. Phys. Chem. (Munich)* **1982**, *133*, 93.

(20) Marcus, R. A. *J. Chem. Phys.* **1956**, *24*, 966. Marcus, R. A. *Annu. Rev. Phys. Chem.* **1964**, *15*, 155. Marcus, R. A. *NATO ASI Ser. C* **1987**, *214*, 45. Marcus, R. A.; Sutin, N. *Biochim. Biophys. Acta* **1985**, *811*, 265.

(21) Sumi, H.; Marcus, R. A. *J. Chem. Phys.* **1986**, *84*, 4894. Jortner, J.; Bixon, M. *J. Chem. Phys.* **1988**, *88*, 167. Kavarnos, G. J.; Turro, N. J. *Chem. Rev.* **1986**, *86*, 401.

(22) Gould, I. R.; Young, R. H.; Moody, R. E.; Farid, S. *J. Phys. Chem.* **1991**, *95*, 2068. Gould, I. R.; Farid, S.; Young, R. H. *J. Photochem. Photobiol., A* **1992**, *65*, 133.

Scheme I



sively.[23] In contrast, there have been few reports concerning azide radical anions.[24] Our findings indicate that the chemical properties of these radical ions depend strongly on the solvent. We studied two limiting cases in detail: the chemistry in protic polar solvents such as methyl alcohol or acetonitrile/water and the reactions in cyclohexane, a nonpolar solvent.

Electron transfer in **1** or **2** generates the linked radical ion pair shown generically in eq 5 of Scheme I. In principle, the radical ion pair will be in an overall singlet or triplet state depending on the spin state of the excited precursor. We attribute no differences to these two spin states since coupling between the spins at long distance will be weak and intersystem crossing will be rapid. Not shown in Scheme I are energy-wasting steps which certainly are present. These steps, internal conversion of the excited state and back electron transfer of the radical ion pair for example, control the quantum efficiency but not the chemical outcome of the reaction.

The data indicate that one of the important reactions of aroyl azide radical anions is loss of nitrogen to form the aroyl nitrene radical anion, eq 6. When the radical ion pair is formed in a polar protic solvent, protonation of the anion to form a cation diradical, eq 7, may be fast enough to compete with nitrogen loss from the azide radical anion. The evidence supporting this postulate comes from the striking difference between the reaction with cyclohexene under nonpolar and polar protic solvent conditions.

A reaction of the nitrene radical anion that competes with its protonation is back electron transfer to generate the neutral nitrene, eq 8. The nitrene is detected from irradiation of **1** or **2** in cyclohexane solution by formation of the secondary amine and, more conclusively, by formation of the aziridine **12** when cyclohexene is present in solution, eq 9. No aziridine is detected when the irradiation is carried out in polar protic solvents that contain cyclohexene. On this basis we conclude that no nitrene is formed in polar protic solution.

The absence of nitrene generation in protic polar solvent could be a consequence of protonation of the azide radical anion as suggested above, or it could be due to protonation of the nitrene radical anion, eq 10, before back electron transfer, eq 8. In the first case, loss of nitrogen from the protonated azide radical anion,

(23) Sekiya, M.; Tomie, M.; Leonard, N. J. *J. Org. Chem.* **1968**, *33*, 318. Seo, E. T.; Nelson, R. F.; Fritsch, J. M.; Marcoux, L. S.; Leedy, D. W.; Adams, R. N. *J. Am. Chem. Soc.* **1966**, *88*, 3498. Ciminale, F.; Curci, R.; Potacci, M.; Troisi, L. *Tetrahedron Lett.* **1988**, *29*, 2463. Döpp, D.; Heufer, J. *Tetrahedron Lett.* **1982**, *23*, 1553. Fujimori, K.; Takata, T.; Fujiwara, S.; Kiuchi, O.; Oae, S. *Tetrahedron Lett.* **1986**, *27*, 1617. Kojo, S.; Morimitsu, K.; Tabushi, I. *Chem. Lett.* **1987**, 2095.

(24) McDonald, R. N.; Chowdry, A. K. *J. Am. Chem. Soc.* **1980**, *102*, 5118. McDonald, R. N.; Chowdry, A. K.; Sester, D. W. *J. Am. Chem. Soc.* **1981**, *103*, 6559. Shields, C. J.; Falvey, D. E.; Schuster, G. B.; Buchardt, O.; Nielsen, P. E. *J. Org. Chem.* **1988**, *53*, 3501.

eq 11, gives the same amide radical as does protonation of the nitrene radical anion. Hydrogen atom abstraction by this amide radical, eq 12, gives an amide and a solvent-derived radical (R·). Finally, the aryl amine radical cation may be reduced by R· (i.e., $CH_2OH^{\cdot} \rightarrow H_2CO + H^+ + e$) to give amide **7**, eq 13, or its demethylation could lead to formation of some of the demethylated products observed at low conversion of the starting bichromophoric compounds.

Examination of the products formed from irradiation of **1** or **2** under various conditions clearly reveals remote activation of the aroyl azide group by long-distance electron transfer. Depending on the reaction conditions, the reduced azide group may be protonated or may lose nitrogen to give, eventually, products either from its reduction or from the reaction of a nitrene.

Conclusions

The mechanism of reaction outlined in Scheme I is consistent with all of the available chemical and spectroscopic data. We cannot rule out the possibility that some nitrene is formed by triplet energy transfer and nitrogen loss. Nevertheless, regardless of this particular mechanistic detail, the general conclusion that remote activation of the azide occurs by electron transfer and that it leads to the expression of azide radical anion, nitrene radical anion, and nitrene reactivity is secure. This finding may prove valuable in the development of labels for biological steroid receptors.

Experimental Section

Materials and Methods. General. Electronic absorption spectra were recorded on a Perkin-Elmer 552 or a Lambda 3 UV–vis spectrophotometer. Electronic emission spectra were recorded on a Spex 1681 Fluorolog spectrophotometer with DM 3000F software at either room temperature or 77 K. Fluorescence lifetimes were measured on a PTI LS-1 luminescence spectrophotometer. Cyclic voltammetry measurements were conducted on a BAS 100B Electrochemical Analyzer (Bioanalytical Systems, Inc.). FTIR spectra were determined with an IBM IR/32 FTIR spectrophotometer. ^1H and ^{13}C NMR spectra were recorded on a Varian XL 200 or a General Electric QE-300 or GN-500 FT-NMR spectrometer. Chemical shifts are reported in δ values with Me_4Si as an internal standard and $CDCl_3$ as solvent for ^1H spectra, and with $CDCl_3$ as reference and solvent for ^{13}C spectra. Mass spectra were obtained with Finnigan-MAT CH5, 731, VG70-VSE, or ZAB-SE mass spectrometers. Mass spectral data are expressed as *m/e* (intensity as percent of the highest ion peak). High-performance liquid chromatography (HPLC) was performed on an IBM Instruments, Inc., LC/9560 ternary gradient liquid chromatograph with a Perkin-Elmer LC-75 absorbance detector. Columns (250 mm × 4 mm i.d.) packed with 5-μm silica or cyanosilica gel were used. Samples were separated by gradient elution in normal phase. LC/MS spectra were obtained on a VG triplet quadrupole system by particle-beam/electron-impact or plasma-spray/electron-impact.

Materials. Unless otherwise noted, materials were obtained from Aldrich Chemical Company, Inc., and were used without further purifications. The solvents used for laser flash photolyses, cyclic voltammetric measurements, and electronic absorption, emission, and excitation analyses were spectrophotometric grade. Acetonitrile was distilled from calcium hydride under nitrogen. Cyclohexane was washed with concentrated sulfuric acid and with water and was distilled from sodium under nitrogen. Cyclohexene was shaken with sodium bisulfite, washed with water, dried over calcium chloride, and then distilled from calcium chloride before use.

Nanosecond Laser Experiments. A Lambda Physik excimer-pumped dye laser system consisting of a PLX 200 excimer laser and an FL 3002 pulsed tunable dye laser was used. The PLX 200 excimer is filled with XeCl and generates 308-nm light. The FL 3002 dye laser consists of a dye oscillator for wavelength control and two amplifiers for power and beam quality enhancement. The dyes BiBuQ and *p*-terphenyl were used to generate 388- (or 380) and 343-nm, ca. 18-ns laser beams, respectively. The probe beam was generated with a xenon flash lamp (15 J) or, for a continuous beam, with a xenon arc lamp (450 W).

Steady-state irradiation at 350 nm was carried out in a Rayonet Reactor (Model RPR-100) equipped with a variable number (to control intensity) of 350-nm lamps (ca. 24 W each). Sample solutions (300–400 mL) were prepared in 30-cm-long and 5-cm-i.d. round-bottom tubes sealed with aluminum foil-covered stoppers. The sample was purged vigorously through a long Teflon tube with N_2 or O_2. After the samples were irradiated, the solvent was evaporated from the samples under reduced pressure. The products were separated by preparative thin-layer chromatography (PLC) and characterized by ^1H NMR and mass spectroscopy. Product yields were determined by analysis of the ^1H NMR spectra and in some cases were confirmed by HPLC measurement.

X-ray Crystallography. Alcohol **3** was dissolved in warm acetone/ether and placed in a chamber containing a flask of hexane. As the hexane slowly diffused into the acetone/ether solution (ca. 1 week), single crystals of **3** formed. The solvent was removed carefully by pipette, and the remaining crystals were washed with ether/hexane and then dried under vacuum. A colorless, transparent, prismatic crystal (ca. 0.3 × 0.6 × 0.6 mm^3) was cut carefully from a larger crystal with slight damage to the (−100) and (010) faces. The sample was found to be in the acentric space group $P\bar{1}$ with 1 molecule per unit cell having dimensions $a = 6.292 \pm 0.001$ Å, $b = 6.398 \pm 0.001$ Å, $c = 15.257 \pm 0.003$ Å, $V = 594.2 \pm 0.3$ Å, $\alpha = 89.268 \pm 0.004°$, $\beta = 82.137 \pm 0.003°$, and $\gamma = 74.081 \pm 0.003°$. The data were collected with a Syntex $P2_1$ four-circle diffractometer equipped with Crystal Logic automation at 27 °C. The structure was solved by direct methods, using SHELXS-86; correct positions for non-H atoms were deduced from the E-map.

3ξ-(*N*-(*p*-Methoxyphenyl)-*N*-methylamino)-5α-androstan-17β-ol (3 and 4). The synthetic procedure follows that described by Abdel-Magid for reductive amination of ketones with sodium triacetoxyborohydride as reducing agent.[25] It gives a 55:45 mixture of cis and trans alcohols with a total yield of 78%. The cis isomer, **3**, was isolated by recrystallization from ether. The cis and trans isomers in the filtrate were separated by flash chromatography with methylene chloride/ethyl acetate/hexane (5:65:30) as eluant. **3**: ^1H NMR ($CDCl_3$) δ 6.84 (s, br, 4 H), 3.76 (s, 3 H), 3.62 (t, 1 H, J = 8.4 Hz), 3.40 (m, 1 H), 2.74 (s, 3 H), 2.04 (m, 1 H), 1.80–0.60 (m, 27 H). **4**: ^1H NMR δ 7.05 (d, 2 H, J = 8.4 Hz), 6.83 (d, 2 H, J = 9.0 Hz), 3.78 (s, 3 H), 3.64 (t, 1 H, J = 8.4 Hz), 3.07 (m, 1 H), 2.65 (s, 3 H), 2.04 (m, 1 H), 1.85–0.70 (m, 27 H). Anal. Calcd for $C_{27}H_{41}NO_2$: C, 78.78; H, 10.04; N, 3.40. Found (**3**): C, 78.79; H, 10.08; N, 3.49. Found (**4**): C, 78.18; H, 10.06; N, 3.29.

3ξ-(*N*-(*p*-Methoxyphenyl)-*N*-methylamino)-5α-androstan-17β-yl 4-(Azidocarbonyl)benzoate (1 and 2). The cis and trans isomers were prepared from the corresponding cis and trans alcohols **3** and **4**. To a stirred solution of terephthaloyl chloride (1.91 g, 9.3 mmol) in 15 mL of dry THF at room temperature was added a solution of **3** (0.72 g, 1.75 mmol) and predried triethylamine (0.4 mL, 2.8 mmol) in THF (ca. 1 mL) over 60 min. The suspension that resulted was heated at reflux for ca. 20 h and then cooled to 5 °C under N_2. A solution of sodium azide (1.2 g, 18 mmol) in 5 mL of water was added. The suspension was stirred for 2 h at ca. 5 °C under N_2. The THF solvent was removed under reduced pressure, and the crude product was dissolved in ether. Insoluble terephthaloyl diazide was removed by filtration. The ether solution was washed with water and saturated brine and dried over magnesium sulfate. The product cis azide, **1**, was purified by flash chromatography with methylene chloride/ethyl acetate/hexane (1:4:16) as eluant to give 0.6 g of white crystal (isolated yield 60%).

The trans azide, **2**, was prepared by the same procedure starting with 0.65 g (1.6 mmol) of **4**, but its purification was more difficult because terephthaloyl diazide and **2** have similar R_f values. Crude **2** was obtained after three flash chromatographies with methylene chloride/ethyl acetate/hexane as eluant in ratios of 7:3:1 to 6:4:1 to 0:1:0 for the three steps, respectively. Pure **2** was obtained after separation on a Chromatotron with methylene chloride/ethyl acetate/hexane (60:2:40) as eluant to give 0.14 g of light-yellow crystals (15%).

Compound **1**: mp 154–157 °C (dec); ^1H NMR ($CDCl_3$) δ 8.09 (s, 4 H), 6.82 (s, br, 4 H), 4.85 (dd, 1 H), 3.77 (s, 3 H), 3.41 (m, 1 H), 2.73 (s, 3 H), 2.30 (m, 1 H), 1.80–0.70 (m, 27 H); MS (FAB, low resolution) *m/e* 585 ($M^{\cdot+}$ + 1, 48); (EI, low resolution) *m/e* 556 ($M^{\cdot+} - N_2$, 40); MS/MS (POSMS) *m/e* 585.5 ($M^{\cdot+}$ + 1, 100), 257.2 (9), 175.1 (5), 161.1 (4), 146.1 (90), 138.1 (60); FTIR (CH_2Cl_2) 2137 (s, doublet), 1717 (s, doublet), 1510 (s), 1250 (s), 1240 (s) cm^{-1}.

Compound **2**: 119–120 °C (dec); ^1H NMR ($CDCl_3$) δ 8.09 (s, 4 H), 7.06 (d, 2 H, J = 8.2 Hz), 6.83 (d, 2 H, J = 8.8 Hz), 4.84 (dd, 1 H), 3.78 (s, 3 H), 3.07 (s, br, 1 H), 2.65 (s, 3 H), 2.30 (m, 1 H), 1.80–0.82 (m, 27 H). Anal. Calcd for $C_{35}H_{44}N_4O_4$: C, 71.89; N, 7.58; N, 9.58. Found (**1**): C, 71.41; H, 7.53; N, 9.55. Found (**2**): C, 72.13; H, 7.72; N, 9.37.

2D NMR Experiments to Determine the Configuration of Steroid-Linked Bichromophoric Compounds 1 and 2. The attached proton test (APT), homoscalar-correlated (COSY), and heteroscalar-correlated (HETCOR) 2D NMR spectra were recorded on a GN-500 FT-NMR spectrometer by standard procedures. The carbon pulse width (90°) was 18 μs. For APT, the spin-echo pulse sequence was used with a post acquisition delay of 2 s, and acquisition time was 0.5 s. Jeener's two-pulse sequence was used for COSY experiments. The pulse width (90°) was ca. 31 μs; postacquisition delay was 1.8 s, and the acquisition time was 0.12 s. In the HETCOR experiments, the carbon pulse width (90°) was

(25) Adel-Magdid, D. F.; Maryanoff, C. A.; Carson, K. G. *Tetrahedron Lett.* **1990**, *31*, 5595.

16 μs and the proton pulse width (90°) through the decoupler was 39 μs. The delay between pulse sequences was 2.5 s.

^{13}C NMR ($CDCl_3$) for **1**: δ 171.91 (C=O), 165.43 (C=O), 145.22 (Ar), 135.70 (Ar), 134.01 (Ar), 131.03 (Ar), 129.69 (ArH, azide), 129.36 (ArH, azide), 116.59 (ArH, anisidine), 114.55 (ArH, anisidine), 84.03 (C17), 60.44 (C3), 55.71 (OMe), 54.35, 50.79, 43.13, 37.04, 35.30, 32.62 (NMe), 31.58, 28.65, 27.68 (C16), 24.90, 23.63 (C2), 20.65 (C4), 12.43 (Me). ^{13}C NMR for **2**: δ 171.94 (C=O), 165.46 (C=O), 155.60 (Ar), 146.66 (Ar), 135.74 (Ar), 133.96 (Ar), 129.69 (ArH, azide), 129.35 (ArH, azide), 124.35 (ArH, anisidine), 114.01 (ArH, anisidine), 84.16 (C17), 57.26 (C3), 55.40 (OMe), 54.47, 50.86, 43.12, 42.39 (NMe), 39.44, 37.07, 36.06, 35.32, 33.22, 31.72, 31.63, 28.43, 27.69 (C16), 24.89, 23.63 (C2), 20.29 (C4), 12.43 (Me). APT for **1**: 165.44, 135.70, 134.01, 43.12, 37.04, 31.57, 31.52, 28.63, 27.68, 23.63, 20.65 with positive phase; 131.04, 129.70, 129.36, 116.62, 114.56, 84.03, 55.71, 54.35, 50.78, 35.29, 12.43 with negative phase. APT for **2**: 171.74, 165.46, 155.60, 146.66, 135.74, 133.96, 43.12, 37.07, 36.07, 33.22, 31.73, 31.64, 28.43, 27.69, 24.88, 23.63, 20.29 with positive phase; 129.70, 129.35, 124.92, 114.02, 84.16, 57.26, 55.41, 54.48, 50.86, 42.39, 39.44, 35.32, 12.43, 12.18 with negative phase. The characteristic COSY off-diagonal signals (cross peaks in ppm) for **1** are (4.85/2.26–2.36), (4.85/1.62–1.68), (3.41/1.64–1.74), and (3.41/1.37–1.45) and for **2** are (4.85/2.26–2.35), (4.85/1.59–1.72), (3.07/1.49–1.55), (3.07/1.44–1.46), and (3.07/1.36–1.41). The overall width of the peak at 3.41 of **1** is 90, 70, and 58 Hz, respectively, in the profile (slice) spectra through the cross peaks at ca. 3.40/3.40, 1.60/1.60, and 1.45/1.45 in the COSY contour plot. The overall width of the peak at 3.07 of **2** is 65, 46, and 46 Hz, respectively, in the slices from the cross sections at 3.10/3.10, 1.50/1.50, and 1.35/1.35 in the COSY contour plot. The characteristic cross peaks (proton/carbon in ppm) of the HETCOR spectra for **1** are (8.09/129.69, 129.36), (6.82/116.59, 114.55), (4.85/84.03), (3.77/55.71), (3.41/60.4), (2.73/32.62), and (2.30/27.68) and for **2** are (8.09/129.70, 129.35), (7.06/124.92), (6.83/114.02), (4.84/84.16), (3.78/55.40), (3.07/57.26), (2.65/42.39), and 2.30 (27.69).

Cyclohexanyl 4-(Azidocarbonyl)benzoate (5). Triethylamine (4.4 mL), dried with potassium hydroxide, was added to a solution of terephthaloyl chloride (28 g, 0.14 mol) in 120 mL of dry THF. The solution, under an N_2 atmosphere, was warmed to 40 °C, and 3.0 mL of cyclohexanol (0.03 mol) was added dropwise with stirring over 30 min. The mixture was stirred at 40 °C for 3 h and then cooled to 0 °C, and a white precipitate was removed by filtration. A solution of sodium azide (82 g, 12 mol) in 120 mL of water was added dropwise to the cooled filtrate with stirring over 2 h. The resulting mixture was added to 500 mL of cold water with stirring. The suspension was filtered, and the solid was dispersed into 700 mL of cold, saturated $NaHCO_3$. The stirred suspension was filtered, and the resulting solid was washed twice with 100 mL of saturated $NaHCO_3$. Finally, the solid was washed with cold water until the pH of the filtrate was 7.0. The resulting solid was dried and then recrystallized from ether (with active carbon) to yield 3.81 g (48%) of **5**: mp 55–57 °C (dec); ^1H NMR ($CDCl_3$) δ 8.11 (d, 4 H, J = 2.4 Hz), 5.04 (m, 1 H), 1.89–2.04 (m, 2 H), 1.73–1.88 (m, 2 H), 1.34–1.66 (m, 6 H); FTIR ($CHCl_3$) 2137 (s), 2182 (w), 1692 (s), 1717 (s) cm^{-1}. Anal. Calcd for $C_{14}H_{15}N_3O_3$: C, 61.53; H, 5.53; N, 15.38. Found: C, 61.81; H, 5.65; N, 15.22.

Irradiation of 1 and 2 in Methanol Solution. A N_2-saturated solution of **1** (or **2**) (ca. 3×10^{-5} M) in 400 mL of methanol was irradiated at 350 nm at ca. −10 °C. The yield of products was determined by ^1H NMR spectroscopic analysis of the crude reaction mixture and by HPLC analysis. The products were separated by PLC with ethyl acetate/hexane/methylene chloride (7:4:1) as eluant. 3α-(*N*-(*p*-Methoxyphenyl)-*N*-methylamino)-5α-androstan-17β-yl 4-(aminocarbonyl)benzoate **7** (from **1**): ^1H NMR ($CDCl_3$) δ 8.10 (d, 2 H, J = 8.4 Hz), 7.87 (d, 2 H, J = 8.4 Hz), 6.83 (s, br, 4 H), 6.13–5.76 (br, 2 H), 4.85 (dd, 1 H), 3.77 (s, 3 H), 3.40 (m, 1 H), 2.73 (s, 3 H), 2.30 (m, 1 H), 1.82–0.70 (m, 27 H); LC/MS (low resolution) m/e 559 ($M^{\cdot+}$ + 1, 17); MS (EI, low resolution) m/e 558 ($M^{\cdot+}$, 15); MS (FAB, low resolution) m/e 559.4 (M^+ + 1, 66). Demethylated amide **7** (from **1** after long irradiation): ^1H NMR ($CDCl_3$) δ 8.10 (d, 2 H, J = 8.4 Hz), 7.87 (d, 2 H, J = 8.4 Hz), 6.94 (m, 2 H), 6.78 (m, 2 H), 6.13–5.76 (br, 2 H), 4.85 (dd, 1 H), 4.04 (m, 1 H), 3.65 (s, 3 H), 3.11 (m, 1 H), 2.30 (m, 1 H), 1.82–0.70 (m, 27 H); LC/MS (low resolution) m/e 545 ($M^{\cdot+}$ + 1, 17); MS (EI, low resolution) m/e 544 ($M^{\cdot+}$, 13). Compound **7** (from **2**): ^1H NMR ($CDCl_3$) δ 8.10 (d, 2 H, J = 8.1 Hz), 7.87 (d, 2 H, J = 8.4 Hz), 7.06 (d, 2 H, J = 8.7 Hz), 6.83 (d, 2 H, J = 9.0 Hz), 5.79–6.15 (br, 2 H), 4.85 (dd, H), 3.78 (s, 3 H), 3.07 (s, br, 1 H), 2.65 (s, 3 H), 2.30 (m, H), 1.80–0.80 (m, 27 H).

3α-(*N*-(*p*-Methoxyphenyl)-*N*-methylamino)-5α-androstan-17β-yl 4-((Methoxycarbonyl)amino)benzoate **8**: ^1H NMR ($CDCl_3$) δ 7.98 (d, 2 H, J = 8.7 Hz), 7.42 (d, 2 H, J = 8.7 Hz), 6.82 (s, br, 5 H), 4.85 (dd, 1 H), 3.80 (s, 3 H), 3.77 (s, 3 H), 3.42 (m, 1 H), 2.73 (s, 3 H), 2.30 (m, 1 H), 1.80–0.70 (m, 27 H); LC/MS m/e 589 ($M^{\cdot+}$ + 1).

Irradiation of 1 and 2 in Cyclohexane Solution. A saturated solution of **1** in ca. 400 mL of N_2-saturated cyclohexane was irradiated at 350 nm at ca. 10 °C. 3α-(*N*-(*p*-Methoxyphenyl)-*N*-methylamino)-5α-androstan-17β-yl 4-((cyclohexylamino)carbonyl)benzoate (**11**, from **1**) was isolated by PLC using ethyl acetate/hexane/methylene chloride (4:8:1) as eluant and identified: ^1H NMR spectroscopy ($CDCl_3$) δ 8.07 (d, 2 H, J = 8.4 Hz), 7.80 (d, 2 H, J = 8.4 Hz), 6.82 (s, br, 4 H), 5.99 (d, 2 H, J = 8.1 Hz), 4.84 (dd, 1 H), 3.99 (m, 1 H), 3.77 (m, 3 H), 3.41 (m, 1 H), 2.73 (s, 3 H), 2.28 (m, 1 H), 2.02 (m, 2 H), 1.79–0.58 (m, 35 H); MS (FAB, low resolution) m/e 641.4 ($M^{\cdot+}$ + 1, 100). After long irradiation of **1**, demethylated amide was isolated by PLC: ^1H NMR ($CDCl_3$) δ 8.07 (d, 2 H, J = 8.4 Hz), 7.79 (d, 2 H, J = 8.2 Hz), 6.76 (d, 2 H, J = 9.0 Hz), 6.59 (d, 2 H, J = 9.0 Hz), 5.99 (d, 1 H, J = 8.1 Hz), 4.82 (dd, 1 H), 3.97 (m, 1 H), 3.74 (s, 3 H), 3.17 (m, 1 H), 2.50–0.70 (m, 38 H); MS (FAB, low resolution) m/e 627.4 ($M^{\cdot+}$ + 1, 100). Compound **11** from **2**: ^1H NMR ($CDCl_3$) δ 8.07 (d, 2 H, J = 8.4 Hz), 7.80 (d, 2 H, J = 8.4 Hz), 7.06 (d, 2 H, J = 8.1 Hz), 6.83 (d, 2 H, J = 9.0 Hz), 6.02 (d, 1 H, J = 7.8 Hz), 4.84 (dd, 1 H), 3.78 (s, 3 H), 3.07 (s, br, 1 H), 2.65 (s, 3 H), 2.28 (m, 1 H), 2.00 (m, 1 H), 1.80–0.82 (m, 37 H).

Irradiation of 1 in Cyclohexane Containing Cyclohexene and Water. A N_2-saturated solution of **1** (ca. 3×10^{-5} M) in cyclohexane containing 10% cyclohexene by volume (400 mL total volume, anhydrous or saturated with water) was irradiated at 350 nm at ca. 10 °C for 10 min. The product was isolated by PLC with ethyl acetate/hexane/methylene chloride (4:8:1) as eluant and analyzed by ^1H NMR spectroscopy. 3α-(*N*-(*p*-Methoxyphenyl)-*N*-methylamino)-5α-androstan-17β-yl 4-((7-azabicyclo[4.1.0]heptan-*N*-yl)carbonyl)benzoate) (**12**): ^1H NMR ($CDCl_3$) δ 8.10 (d, 2 H, J = 8.4 Hz), 8.02 (d, 2 H, J = 8.4 Hz), 6.82 (s, br, 4 H), 4.85 (dd, H), 3.76 (s, 3 H), 3.41 (m, H), 2.77 (d, 2 H, J = 3.0 Hz), 2.73 (s, 3 H), 2.28 (m, H), 2.05–0.69 (m, 35 H); MS (FAB, low resolution) m/e 639.3 (M^+ + 1, 100).

Irradiation of 1 in Acetonitrile Solution Containing Cyclohexene. A N_2-saturated solution of **1** (ca. 3×10^{-5} M) in acetonitrile containing 10% (v/v) of cyclohexene was irradiated at 350 nm at ca. 5 °C for 10 min. The products were isolated by PLC using ethyl acetate/hexane/methylene chloride (6:4:1) as eluant and identified by ^1H NMR spectroscopy as amide **7** (40% at 65% conversion; ca. 25% of the product was demethylated). No **12** was detected in the reaction mixture either by NMR spectroscopy of the crude mixture or by PLC/MS analysis.

Acknowledgment. This work was supported by a grant from the National Institutes of Health, for which we are grateful. Dr. S. Wilson of the University of Illinois School of Chemical Sciences X-ray facility assisted in the determination of the crystal structure of **3**. Dr. V. Mainz of the University of Illinois School of Chemical Sciences Molecular Spectroscopy Laboratory assisted with the 2D NMR spectral analyses.