Laser Flash Photolysis Measurements of the Kinetics of Carbon−Nitrogen Bond Rotations in α-Amide Radicals

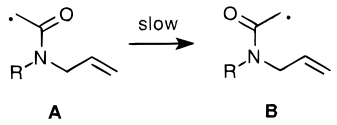
Osama M. Musa, John H. Horner,* and Martin Newcomb*

Department of Chemistry, Wayne State University, Detroit, Michigan 48202

Received July 31, 1998

α-Amide radicals are important for radical-based synthetic methodology for several reasons. They are relatively simple to generate by radical addition to an acrylamide or by atom or group abstraction or homolytic fragmentation from the α-position of an amide, and they have proven to be especially useful in the rapidly evolving area of acyclic stereochemical control of radical reactions.[1,2] The utility of α-amide radicals in diastereoselective reactions is related to the rate constants for conformational equilibration of these species. Although rapid on the laboratory time scale, the rate of rotation of the C−C bond between the carbonyl and α-carbon atoms of an α-amide radical is slow in comparison to that of many radical reactions, with a rate constant of about 2×10^4 s^{-1} at ambient temperature.[3] Thus, in many cases, the populations of C−C conformational isomers of an α-amide radical will be fixed in the initial reactions that generate these species, and control of these populations could have a profound effect on diastereoselectivity.

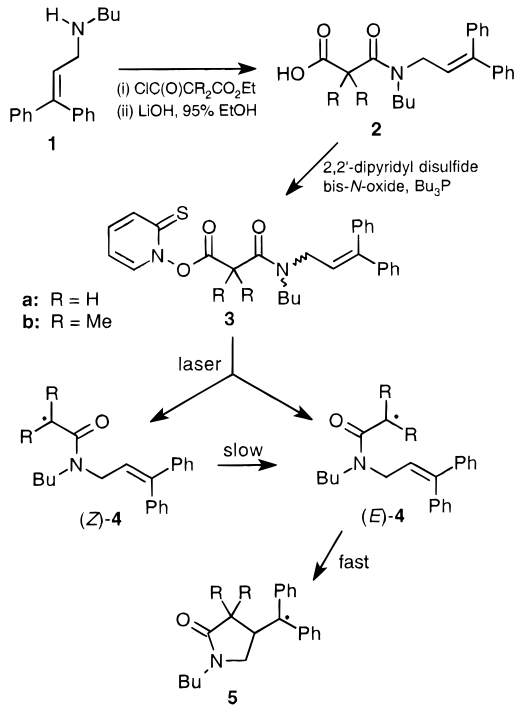
The rate constants for conformational interconversions by rotations about the carbonyl carbon to nitrogen bonds of α-amide radicals have not been determined previously, but it is clear that C−N bond rotations are also important. Relatively slow C−N bond rotation will affect the diastereoselectivity of reactions of unsymmetrically *N*-substituted α-amide radicals in a manner similar to that of slow C−C bond rotation. Curran and Tamine demonstrated that the production of lactams by cyclizations of α-amide radicals containing allylic groups on nitrogen can be partially limited by slow C−N bond rotation that isolates conformer **A** which cannot cyclize from conformer **B** which can.[4] One can deduce from the results of Curran and Tamine that C−N rotation rate constants are somewhat larger than those for C−C bond rotation.[4] We report here the results of laser flash photolysis (LFP) kinetic studies which confirm that deduction.



Results and Discussion

The experimental concept (Scheme 1) is related to the preparative studies reported by Curran and Tamine.[4]

Scheme 1



PTOC ester radical precursors **3** were prepared from the corresponding malonate monoamides **2** by methods similar to those used for the synthesis of related α-amide radical precursors.[5] PTOC ester **3a** was especially unstable, and crude samples were used in kinetic studies. Laser irradiation (355 nm) of precursors **3** gave α-amide radicals **4** by homolysis of the N−O bond of the PTOC ester and instant (on the ns time scale) decarboxylation of the acyloxyl radicals thus formed. Cyclizations of radicals **4** gave diphenylalkyl radicals **5** that have long wavelength λ_{max} in the 330−334 nm range as expected[6] and were readily monitored by UV spectroscopy. Figure 1 shows the time-resolved spectrum of **5b** from reaction of radical **4b**.

The LFP experimental design was the same as that recently described.[7] Dilute solutions of PTOC esters **3** were thermally equilibrated, sparged with helium, and allowed to flow through a flow cell in the kinetic spectrometer. Temperatures were measured with a thermocouple in the flowing stream. Rate constants for formation of radicals **5** were determined in THF at various temperatures. Because radicals **4** were symmetrically substituted at the α-carbon, there was no possibility of C−C conformers that react with different rate constants.

5-*exo* cyclizations of radicals containing the diphenylethenyl moiety are quite rapid, and radicals (*E*)-**4** were expected to cyclize with rate constants of about 1×10^8

(1) Porter, N. A.; Giese, B.; Curran, D. P. *Acc. Chem. Res.* **1991**, *24*, 296−304.
(2) Curran, D. P.; Porter, N. A.; Giese, B. *Stereochemistry of Radical Reactions: Concepts, Guidelines, and Synthetic Applications*; VCH: Weinheim, 1995.
(3) Strub, W.; Roduner, E.; Fischer, H. *J. Phys. Chem.* **1987**, *91*, 4379−4383.
(4) Curran, D. P.; Tamine, J. *J. Org. Chem.* **1991**, *56*, 2746−2750.
(5) Musa, O. M.; Choi, S. Y.; Horner, J. H.; Newcomb, M. *J. Org. Chem.* **1998**, *63*, 786−793.
(6) Chatgilialoglu, C. In *Handbook of Organic Photochemistry*; Scaiano, J. C., Ed.; CRC Press: Boca Raton, FL, 1989; Vol. 2; pp 3−11.
(7) Horner, J. H.; Tanaka, N.; Newcomb, M. *J. Am. Chem. Soc.* **1998**, *120*, 10379−10390.

10.1021/jo981538e CCC: $18.00
Published on Web 02/05/1999

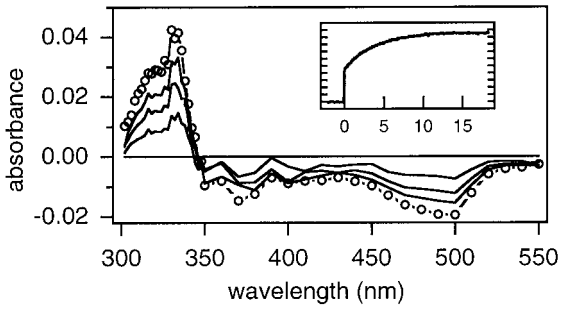


Figure 1. Time-resolved spectrum from reaction of radical **4b** at 19.9 °C. The traces are at 1.0, 1.8, 2.6, and 4.2 μs after laser irradiation with data at 0.2 μs subtracted to give a baseline. Radical **4b** is growing in with λ_{max} at 332 nm, and the byproduct radical from the photolysis, 2-pyridinethiyl with λ_{max} at 490 nm, is decaying. Symbols for the 4.2 μs data show the wavelengths monitored. The inset shows the kinetic trace at 330 nm; the *x*-axis is time in microseconds.

Table 1. Observed Rate Constants for the Slow Reactions of Radicals 4

		$10^{-5}k_{obs}$[b] (s^{-1})	
radical	temp[a] (°C)	set 1	set 2
4a	10.1	3.12 ± 0.10	3.11 ± 0.21
	19.8	5.00 ± 0.16	4.82 ± 0.12
	29.3	7.48 ± 0.49	8.13 ± 0.52
	38.5	12.5 ± 0.8	12.5 ± 0.8
	46.3	15.8 ± 1.2	17.4 ± 1.3
4b	2.2	0.89 ± 0.07	0.86 ± 0.10
	11.0	1.61 ± 0.07	1.58 ± 0.07
	19.9	2.51 ± 0.09	2.67 ± 0.05
	30.0	4.79 ± 0.13	4.69 ± 0.39
	40.2	8.35 ± 0.15	8.03 ± 0.29
	47.9	12.1 ± 0.5	11.9 ± 1.0

[a] ±0.3 °C. [b] Errors are 2σ.

s^{-1} at ambient temperature.[5,8−10] Radicals (*Z*)-**4**, on the other hand, cannot cyclize. If C−N bond rotation in radicals **4** is slower than cyclization of (*E*)-**4**, then one should observe rapid (possibly instant on the ns time scale) signal growth from cyclization of (*E*)-**4** followed by slower growth resulting from rotation of conformer (*Z*)-**4** to (*E*)-**4** followed by cyclization.

The expected double signal growth was found for both radicals **4**. The fast reaction was too rapid to measure at ambient temperature. The inset in Figure 1 shows a kinetic trace at 19.9 °C taken near λ_{max} of **5b**; "instant" signal growth from cyclization of (*E*)-**4b** in the first 100 ns is followed by slower growth over several microseconds. At lower temperatures, the fast reaction could be measured; for example, the rate constant for radical **4a** was 5×10^7 s^{-1} at −46 °C and that for **4b** was 5×10^7 s^{-1} at −40 °C. The demonstration that the fast reactions are more than 2 orders of magnitude faster than the slow reactions (see below) is important for two reasons. It shows that the kinetics of the slow processes will not be convoluted with those of the fast processes and it requires that rotations of the $(Z)_{CN}$ conformers to the $(E)_{CN}$ conformers are effectively irreversible.

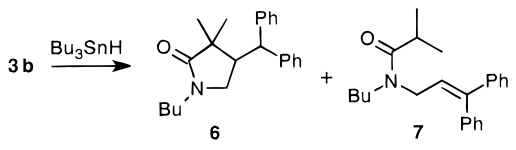
Table 1 contains the kinetic results for the slow processes for radicals **4**. The rate constants are in the range of 10^5−10^6 s^{-1}. LFP kinetic studies with a nanosecond-resolution apparatus are quite accurate in this range. The response time of our apparatus introduces insignificant errors when $k_{obs} < 5 \times 10^7$ s^{-1}, and bimolecular processes (radical−radical reactions and reactions of radicals with residual oxygen) are not important because they have pseudo-first-order rate constants of $< 1 \times 10^4$ s^{-1}. The LFP rate constants for first-order processes are also precise because hundreds of data points are obtained in the LFP study.

The rate constants for the slow reactions of radicals **4** give the Arrhenius functions in eqs 1 and 2, where errors are at 2σ and $\theta = 2.3RT$ kcal/mol. The log *A* parameters are those expected for rotational processes which have little entropic demand (log *A* at 300 K is 13.1 for a process with $\Delta S^{\ddagger} = 0$) as opposed to the organized transition states of 5-*exo* cyclizations which result in log *A* values of 9−10. Rate constants for C−N rotations at 20 °C calculated from eqs 1 and 2 are 5.1×10^5 s^{-1} for **4a** and 2.7×10^5 s^{-1} for **4b**. The C−N bond rotations in α-amide radicals are somewhat more than an order of magnitude faster than the C−C bond rotations between the carbonyl carbon and α-carbon.[3]

$$(\text{for } \mathbf{4a})\ \log(k \times s) = (12.01 \pm 0.26) - (8.44 \pm 0.38)/\theta \quad (1)$$

$$(\text{for } \mathbf{4b})\ \log(k \times s) = (12.94 \pm 0.13) - (10.06 \pm 0.17)/\theta \quad (2)$$

To demonstrate the significance of the C−N bond rotation in synthesis, we conducted reactions with PTOC ester **3b** in benzene at 20 °C in the presence of Bu_3SnH at relatively high (1.2 M) and lower (0.6 M) concentrations of tin hydride. The rate constant for tin hydride reaction with a 2° α-amide radical at 20 °C is 3×10^6 M^{-1} s^{-1},[5] but we assumed that the rate constant for Bu_3SnH reaction with a 3° α-amide radical will be smaller than this on the basis of results with 2° and 3° α-ester radicals which show such an effect.[8] Accordingly, Bu_3SnH was expected to react with α-amide radical **4b** with a pseudo-first-order rate constant that is greater than the first-order rate constant for C−N rotation in the high Bu_3SnH concentration experiment. Because the cyclization of radical (*E*)-**4b** is much faster than both tin hydride trapping and C−N rotation, essentially all (*E*)-**4b** initially produced or formed by rotation of (*Z*)-**4b** will cyclize. In practice, the reaction in the presence of 1.2 M Bu_3SnH gave an 80:20 ratio of lactam **6** to acyclic amide **7** as determined by GC, whereas at 0.6 M Bu_3SnH the ratio of **6** to **7** increased to 92:8.



The C−N bond rotation in **4b** can be used as a radical clock[11,12] to calculate the rate constant for tin hydride trapping from the above results. The initial populations

(8) Newcomb, M.; Horner, J. H.; Filipkowski, M. A.; Ha, C.; Park, S. U. *J. Am. Chem. Soc.* **1995**, *117*, 3674−3684.
(9) Johnson, C. C.; Horner, J. H.; Tronche, C.; Newcomb, M. *J. Am. Chem. Soc.* **1995**, *117*, 1684−1687.
(10) Horner, J. H.; Martinez, F. N.; Musa, O. M.; Newcomb, M.; Shahin, H. E. *J. Am. Chem. Soc.* **1995**, *117*, 11124−11133.
(11) Griller, D.; Ingold, K. U. *Acc. Chem. Res.* **1980**, *13*, 317−323.
(12) Newcomb, M. *Tetrahedron* **1993**, *49*, 1151−1176.

of (*E*)- and (*Z*)-**4b** produced in radical chain reactions of the PTOC ester **3b** are not known, but we assume that they are about equal. For an initial isomer ratio of 1:1, the product ratios indicate that tin hydride trapping was 0.66 times as fast as rotation at 1.2 M Bu_3SnH and 0.19 times as fast as rotation at 0.6 M Bu_3SnH. With an adequate number of data points, one could determine accurately both the initial populations of conformers and the rate constant for Bu_3SnH reaction with **4b**, but an approximate rate constant for tin hydride trapping of the 3° amide radical at 20 °C of 1×10^5 M^{-1} s^{-1} one calculates from these results should be useful for synthetic planning purposes.

The very fast 5-*exo* cyclizations of the $(E)_{CN}$ conformers of radicals **4** also provide some useful kinetic information. The reactions were too fast for measurements over a wide temperature range, but one can assume that these cyclization reactions will have log *A* parameters similar to those of related radicals, or log $A \approx 9.5$. Using this value and measured rate constants for cyclizations of radicals (*E*)-**4** at low temperatures, one calculates approximate rate constants for cyclization at ambient temperature of 2×10^8 and 1×10^8 s^{-1} for **4a** and **4b**, respectively. The diphenylethenyl group typically accelerates 5-*exo* radical cyclizations at ambient temperature by about a factor of 200,[5] so one would estimate that the simple analogues of radicals **4** with terminal vinyl groups will cyclize at ambient temperature with rate constants in the range of 0.5×10^6 to 1.0×10^6 s^{-1}, or about 1 order of magnitude larger than those for C−N bond rotation. Thus, tin hydride in high concentrations might trap considerable amounts of the $(E)_{CN}$ conformers of simple terminal vinyl analogues of **4** in competition with cyclization.

In comparison to other radical intermediates, the α-amide radicals are among the better understood from a kinetic perspective with rate constants for conformer interconversions,[3] cyclizations,[5] and reactions with tin hydride[5] available. In addition, a simple α-amide radical clock based on the 5-hexenyl radical cyclization has been calibrated[5] and can be used for timing bimolecular reactions in indirect competition studies.[12] In many cases, one can take advantage of the known kinetics to predict the outcomes of synthetic reactions.

Even without a detailed prospective kinetic analysis, one should appreciate two important consequences of the rate constants for C−N bond rotations of α-amide radicals. The first-order rate constants for these rotations are quite similar to the pseudo-first-order rate constants one will have in many bimolecular reactions of radicals; therefore, it should often be possible to express or suppress the rotational process as desired by changing the concentration of a reagent, as we demonstrated in the tin hydride reactions with radical **4b**. In addition, the low entropy demand for the C−N rotation is important. Bimolecular reactions have log *A* parameters of about 9 whereas the C−N rotations have log *A* of 12−13. As reaction temperatures are increased, the rotations will become increasingly competitive with bimolecular reactions. Curran and Tamine clearly appreciated that fact when they suggested that one should "heat it up" to improve yields of lactams from 5-*exo* cyclizations.[4] If instead one wishes to prevent conformer equilibration in order to improve diastereoselectivity, as in radical production from a conformationally biased precursor, one should "cool it down".

Experimental Section

General. NMR spectra were recorded at 300 or 500 MHz (^1H) and 75 or 125 MHz (^{13}C). Radial chromatography was performed on a model 7924T Chromatotron (Harrison Research). Tri-*n*-butyltin hydride was prepared by the method of Hayashi et al.[13] Tetrahydrofuran (THF) was distilled under a nitrogen atmosphere from sodium benzophenone ketyl. Methylene chloride was distilled under nitrogen from phosphorus pentoxide. Benzene was distilled under nitrogen from calcium hydride. High-resolution mass spectral analyses were conducted by the staff of the Central Instrument Facility at Wayne State University.

***N*-Butyl-3,3-diphenyl-2-propenylamine (1).** To butylamine (27.14 mL, 274.5 mmol) in 15 mL of THF was added dropwise 3-bromo-1,1-diphenyl-1-propene[14] (1.5 g, 5.49 mmol). The mixture was allowed to stir overnight at room temperature. The THF was removed under reduced pressure, and the residue was partitioned between ether and water. The organic layer was separated, dried over $MgSO_4$, and filtered, and the solvent was removed under reduced pressure to give 1.36 g of **1** as a yellow oil (5.13 mmol, 94%). ^1H NMR: δ 7.42−7.17 (m, 10 H), 6.20 (t, 1 H, $J = 6.9$ Hz), 3.32 (d, 2 H, $J = 6.9$ Hz), 2.58 (t, 2 H, $J = 6.9$ Hz), 1.47−1.28 (m, 5 H), 0.90 (t, 3 H, $J = 7.5$ Hz). ^{13}C NMR: δ 143.08, 142.17, 139.71, 129.74, 128.39, 128.14, 128.09, 127.34, 127.24, 127.15, 49.26, 48.65, 32.25, 20.45, 13.98. HRMS: calcd for $C_{19}H_{23}N$, 265.1831; found, 265.1837.

***N*-Butyl-*N*-(3,3-diphenyl-2-propenyl)malonamic acid ethyl ester** was prepared by slowly adding chlorocarbonylacetic acid ethyl ester[15] (0.22 g, 1.47 mmol) to a stirred solution of amide **1** (0.39 g, 1.47 mmol), Et_3N (0.15 g, 1.47 mmol), and DMAP (0.018 g, 1.47 mmol) in CH_2Cl_2 (15 mL) at room temperature. The mixture was stirred for 2 h. Water was added, and the resulting mixture was extracted three times with ether. The combined ethereal extracts were washed with a saturated aqueous NaCl solution, dried over $MgSO_4$, filtered, and concentrated under reduced pressure. Column chromatography (hexanes−EtOAc, 3:1) gave 0.45 g of the title ester as a yellow oil (1.19 mmol, 81%). Complex ^1H and ^{13}C NMR spectra due to slow conformer rotation are provided in Supporting Information. HRMS: calcd for $C_{24}H_{29}NO_3$, 379.2147; found, 379.2144.

***N*-Butyl-*N*-(3,3-diphenyl-2-propenyl)malonamic Acid (2a).** The above ethyl ester (0.076 g, 0.20 mmol) and LiOH (0.033 g, 0.80 mmol) in 95% EtOH (10 mL) were heated at reflux for 5 h. The mixture was cooled and concentrated. The residue was dissolved in water, and the resulting solution was acidified with HCl. The mixture was extracted three times with ether, and the combined ethereal extracts were washed with a saturated aqueous NaCl solution, dried over $MgSO_4$, and concentrated under reduced pressure. Column chromatography (hexanes−EtOAc, 1:1) gave 0.066 g of **2a** as an oil (0.19 mmol, 94.3%). Complex ^1H and ^{13}C NMR spectra due to slow conformer rotation are provided in Supporting Information.

***N*-Butyl-*N*-(3,3-diphenyl-2-propenyl)malonamic Acid 2-Thioxo-2*H*-pyridine-1-yl Ester (3a).** To a solution of malonamic acid **2a** (0.062 g, 0.18 mmol) and 2,2′-dipyridyl disulfide bis-*N*-oxide[16] (0.05 g, 0.194 mmol) in dry CH_2Cl_2 (10 mL) in a flask wrapped with aluminum foil was added tributylphosphine (0.05 mL, 0.194 mmol) at 0 °C under N_2. The reaction was stirred at room temperature for 2 h before aqueous Na_2CO_3 (10%, 10 mL) was added. The organic layer was separated, and the aqueous layer was extracted with CH_2Cl_2 three times. The combined organic extracts were washed with brine, dried over $MgSO_4$, and concentrated under reduced pressure. The crude samples appeared to contain approximately equal amounts of the desired PTOC ester and *N*-hydroxypyridine-2-thione (from hydrolysis of the PTOC ester) in addition to Bu_3P. Attempts to purify the crude material by chromatography resulted in extensive decomposition. Kinetic studies were performed with crude samples used immediately after preparation and NMR analysis.

(13) Hayashi, K.; Iyoda, J.; Shiihara, I. *J. Organomet. Chem.* **1967**, *10*, 81−94.
(14) Davis, M. A.; Herr, F.; Thomas, R. A.; Charest, M. P. *J. Med. Chem.* **1967**, *10*, 627−636.
(15) Holmquist, B.; Bruice, T. C. *J. Am. Chem. Soc.* **1969**, *91*, 2993−3002.
(16) Barton, D. H. R.; Samadi, M. *Tetrahedron* **1992**, *48*, 7083−7090.

***N*-Butyl-*N*-(3,3-diphenyl-2-propenyl)dimethylmalonamic acid ethyl ester** was prepared by slowly adding 2-chlorocarbonyl-2-methylpropanoic acid ethyl ester[15] (0.48 g, 3.02 mmol) to a stirred solution of amine **1** (0.80 g, 3.02 mmol), Et_3N (0.31 g, 3.02 mmol), and DMAP (0.04 g, 0.30 mmol) in CH_2Cl_2 (15 mL) at room temperature. The mixture was stirred for 2 h. Water was added, and the resulting mixture was extracted three times with ether. The combined ethereal extracts were washed with a saturated aqueous NaCl solution, dried over $MgSO_4$, filtered, and concentrated under reduced pressure. Column chromatography on silica gel (hexanes−EtOAc, 3:1) gave 0.51 g of the desired ester as an oil (1.24 mmol, 71%). Complex ^1H and ^{13}C NMR spectra due to slow conformer rotation are provided in Supporting Information. HRMS: calcd for $C_{26}H_{33}NO_3$, 407.2461; found, 407.2466.

***N*-Butyl-*N*-(3,3-diphenyl-2-propenyl)dimethylmalonamic Acid (2b).** The above ester (0.28 g, 0.69 mmol) and LiOH (0.11 g, 2.74 mmol) in 95% EtOH (10 mL) were heated at reflux for 5 h. The mixture was cooled and concentrated. The residue was dissolved in water, and the resulting solution was acidified with HCl. The mixture was extracted three times with ether, and the combined ethereal extracts were washed with a saturated aqueous NaCl solution, dried over $MgSO_4$, and concentrated under reduced pressure. Column chromatography on silica gel (hexanes−EtOAc, 1:1) gave 0.20 g of **2b** as an oil (0.52 mmol, 95%). Complex ^1H and ^{13}C NMR spectra due to slow conformer rotation are provided in Supporting Information.

***N*-Butyl-*N*-(3,3-diphenyl-2-propenyl)dimethylmalonamic Acid 2-Thioxo-2*H*-pyridine-1-yl Ester (3b).** To a solution of acid **2b** (0.10 g, 0.264 mmol) and 2,2′-dipyridyl disulfide bis-*N*-oxide[16] (0.073 g, 0.29 mmol) in dry CH_2Cl_2 (10 mL) in a flask wrapped with aluminum foil was added tributylphosphine (0.073 mL, 0.29 mmol) at 0 °C under N_2. The reaction was stirred at room temperature for 2 h before aqueous Na_2CO_3 (10%, 10 mL) was added. The organic layer was separated, and the aqueous layer was extracted with CH_2Cl_2 three times. The combined organic extracts were washed with brine, dried over $MgSO_4$, and concentrated under reduced pressure. Column chromatography on silica gel (hexanes−EtOAc, 1:1) gave 0.09 g of PTOC ester **3b** as a yellow oil (0.18 mmol, 68%). Complex ^1H and ^{13}C NMR spectra due to slow conformer rotation are provided in Supporting Information.

***N*-Butyl-3,3-dimethyl-4-(diphenylmethyl)-2-pyrrolidinone (6)** was isolated from the reaction of PTOC ester **3b** (0.044 g, 0.09 mmol) and Bu_3SnH (0.052 g, 0.18 mmol) in 3.0 mL of dry THF. The reaction mixture was sealed with a septum, flushed with nitrogen, and photolyzed with visible light for 1 h at room temperature. Radial chromatography on silica gel (hexane−EtOAc, 3:1) gave 0.015 g of lactam **6** as an oil (0.045 mmol, 50%). ^1H NMR: δ 7.42−7.13 (m, 10 H), 3.88 (d, 1 H, J = 13 Hz), 3.20−3.36 (m, 1 H), 3.08−3.14 (m, 1 H), 2.92−3.00 (m, 1 H), 2.82 (t, 2 H, J = 11 Hz), 1.16−1.44 (m, 4 H), 1.04 (s, 3 H), 0.84−0.94 (m, 3 H), 0.76 (s, 3 H). ^{13}C NMR: δ 143.2, 142.9, 128.9, 128.6, 128.2, 127.6, 126.85, 126.78, 52.8, 49.4, 47.2, 43.9, 42.3, 29.3, 25.2, 20.0, 18.7, 13.8 (carbonyl C not observed). HRMS: calcd for $C_{23}H_{29}NO$, 335.2249; found, 335.2251.

***N*-Butyl-*N*-(3,3-diphenyl-2-propenyl)-2-methylpropanamide (7).** Amine **1** (1.03 g, 3.89 mmol) and Et_3N (0.65 mL, 4.67 mmol) were added dropwise to a solution of isobutyryl chloride (0.49 mL, 4.67 mmol) in diethyl ether (20 mL) at 0 °C. The solution was stirred for 12 h. After filtration of the ammonium salts, the filtrate was washed with water, saturated $NaHCO_3$, and saturated NaCl. The organic layer was dried over $MgSO_4$, filtered, and concentrated under reduced pressure. Column chromatography on silica gel (hexanes−EtOAc, 3:1) gave 0.98 g of acyclic amide **7** as an oil (2.93 mmol, 75%). Complex ^1H and ^{13}C NMR spectra due to slow conformer rotation are provided in Supporting Information. HRMS: calcd for $C_{23}H_{29}NO$, 335.2249; found, 335.2250.

Kinetic Studies. LFP studies in THF were accomplished as previously described;[7] each "set" in Table 1 is an independent value determined by summing 10−15 runs to improve the signal-to-noise ratio. Indirect kinetic studies of the reaction of **3b** in the presence of Bu_3SnH were performed as described;[5] the reaction mixtures were analyzed on a GC equipped with a TC detector, and yields of **6** and **7** were calculated against an internal standard of eicosane using response factors determined with authentic samples.

Acknowledgment. This work was supported by a grant from the National Science Foundation (CHE-9614968). We thank Prof. D. P. Curran for suggesting these experiments and Mr. N. Miranda, Mr. I. Samano, Mr. R. Gappy, and Ms. M. Nguyen for experimental assistance.

Supporting Information Available: ^1H and ^{13}C NMR spectra (16 pages). This material is contained in libraries on microfiche, immediately follows this article in the microfilm version of the journal, and can be ordered from the ACS; see any current masthead page for ordering information.

JO981538E