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Conical Intersection Control of Heterocyclic Photochemical Bond Scission[1,2]

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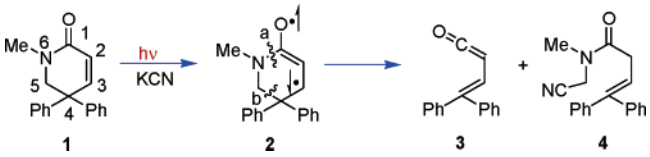
Abstract: The photochemistry of the heterocycle 5,6-dihydro-1-methyl-5,5-diphenylpyridin-2(1*H*)-one (compound **1** in the text) leads to two competitive reactions (the reactions are depicted in the Introduction to the article). These arise from fission of bond **a**, between the nitrogen (N-6) and C-1, and bond **b**, between C-4, with the two phenyl substituents, and C-5, adjacent to the nitrogen. Scission of bond **a** alone leads to a zwitterionic intermediate which can be trapped by nucleophiles, while cleavage of bonds **a** and **b** together affords two fragments—a ketene and an imine. The ketene could be intercepted with nucleophiles and the imine trimerized. Computation reveals little weakening of bonds **a** and **b**. But as stretching begins, conical intersections are encountered, leading to ground-state products.

Introduction

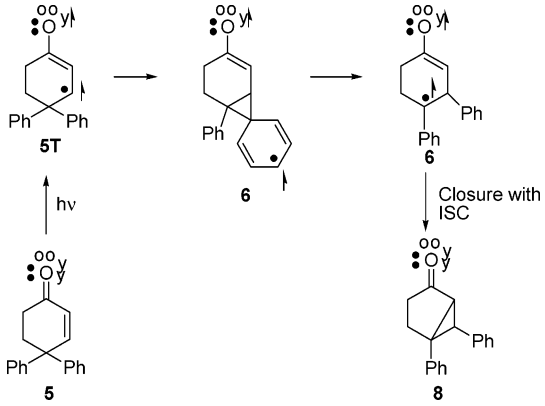
Most recently we have encountered some intriguing new photochemistry.

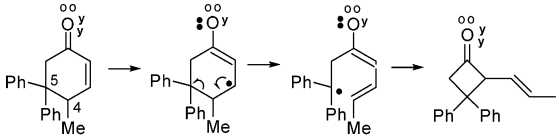


In contrast, most of our past photochemical research has concentrated on carbocyclic systems, and heavily on their rearrangements.[3] In the present study we turned to the chemistry of heterocyclic counterparts. The usual reaction of 4-aryl-substituted cyclohexenones is the ubiquitous "Type-B enone rearrangement",[4] in which an aryl group at C-4 migrates to C-3[4] (Scheme 1).

Less common, but fascinating, is the diversion of the reaction course when carbon-5 is appropriately substituted. Thus, if there is substitution at C-5 which is capable of stabilizing odd-electron density at this carbon, then commonly[5] scission of bond 4−5 results, as shown in eq 1, where an electron at C-5 is stabilized by two phenyl groups. More recent research has provided some aza-steroid examples which might be interpreted similarly.[5c] This research has involved heterocyclic photochemistry, and the question arose whether a nitrogen bonded to C-5 might be playing a similar role. Our previous observation[6] suggests that possibility.

Scheme 1. Mechanism of the Type B Rearrangement





(1)

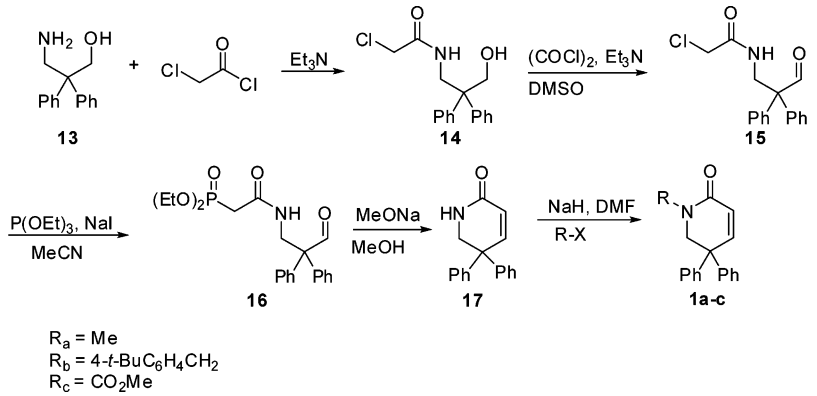
Results

We began with a study of monocyclic heterocycles having nitrogen substitution as part of the ring structure. The synthesis is outlined in Scheme 2. The desired six-membered heterocyclic ring closure was obtained nicely by an intramolecular Horner−Emmons cyclization of phosphonate **16**.

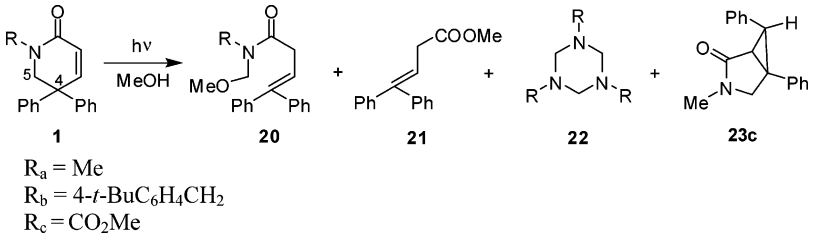
Two photoproducts, **20a** and **21**, were observed upon direct photolysis of **1a** in methanol (Scheme 3). Parallel photolyses

(1) This is Paper 282 of our General Series.
(2) Zimmerman, H. E.; Cheng, J. *J. Org. Chem.* **2006**, *71*, 873−882.
(3) For recent references, see: (a) Zimmerman, H. E.; Nesterov, E. E. *J. Am. Chem. Soc.* **2003**, *125*, 5422−5430. (b) Zimmerman, H. E.; Sereda, G. A. *J. Org. Chem.* **2003**, *68*, 283−292. (c) Zimmerman, H. E.; Novak, T. *J. Org. Chem.* **2003**, *68*, 5056−5066.
(4) (a) Zimmerman, H. E.; Wilson, J. W. *J. Am. Chem. Soc.* **1964**, *86*, 4036−4042. (b) Zimmerman, H. E.; Rieke, R. D.; Scheffer, J. R. *J. Am. Chem. Soc.* **1967**, *89*, 2033−2047. (c) Zimmerman, H. E.; Hancock, K. G. *J. Am. Chem. Soc.* **1968**, *90*, 3749−3760.
(5) (a) Zimmerman, H. E.; Solomon, R. D. *J. Am. Chem. Soc.* **1986**, *108*, 6276−6289. (b) Zimmerman, H. E.; Sam, D. J. *J. Am. Chem. Soc.* **1966**, *88*, 4114−4116. (c) Canovas, A.; Fronrodona, J.; Bonet, J.-J. *Helv. Chim. Acta* **1980**, *63*, 2380−2389. (d) Zimmerman, H. E.; Morse, R. L. *J. Am. Chem. Soc.* **1968**, *90*, 954−966.
(6) Zimmerman, H. E.; Pushechnikov. A. *Org. Lett.* **2004**, *6*, 3779−3780.

Scheme 2. Synthesis of Heterocyclic Reactants



Scheme 3. Photochemistry of the Three Heterocycles

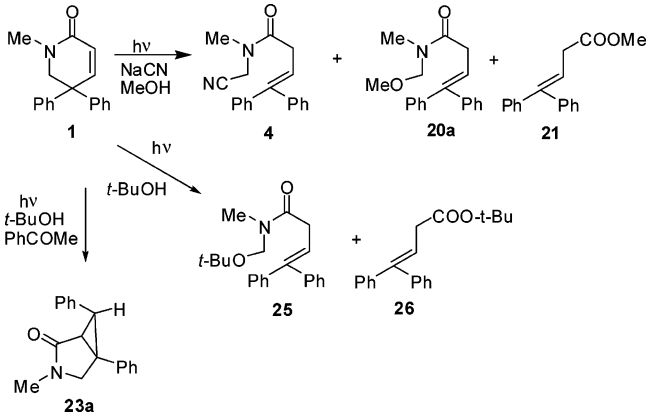


were run in *tert*-butyl alcohol with similar results. No identifiable products were observed with benzene as a solvent. We note that photoproduct **20a** has arisen from fission of bond 4−5, a result we encountered in one earlier study.[6] However, we observe that photoproduct **21** arises from fission of bond 1−6 in addition to 4−5. To ensure the isolation of all the products of this reaction, compound **1b**, having a bulky 4-*tert*-butylbenzyl substituent at nitrogen, was prepared and photolyzed. Indeed, the isolation of the trimeric product **22b** proved possible.

In addition, the photolysis of heterocycle **1c**, with an electron-withdrawing group on nitrogen, was run in methanol. In this case, beside the expected products **20c** and **21**, the bicyclic compound **23c** was identified, and it was the only product when the reaction was run in benzene. The structure of product **23c** was established by X-ray analysis. We note that this is a common Type B rearrangement product (Scheme 1). Such a diversity in reactivity urged us to investigate the reaction multiplicity. For this purpose, the photolysis of **1a** in the presence of acetophenone as a sensitizer was run in *tert*-butyl alcohol. Bicyclic compound **23a** was isolated then as the sole product. Since it was an oil, its structure was established by synthesis involving saponification and subsequent methylation of compound **23c**. Thus, we conclude that products **20**, **21**, and **22** derive from a singlet (i.e., S1) reaction, and product **23** comes from a triplet.

With the intent of trapping intermediates and helping to establish the reaction mechanism, the photolysis of **1a** in methanol with the addition of potassium cyanide was performed. Photoproduct **4** was formed and clearly had arisen from cyanide attack in competition with methanol, as shown in Scheme 4. The mechanism remains to be discussed (vide infra).

Scheme 4. Photolyses as a Function of Reaction Conditions



Results

Computational Aspects and Methodology. In parallel with our experimental efforts, and in order to better understand the reaction course, we turned to ab initio computations. We employed CASSCF(6,6) with a 6-31g(d) basis set in Gaussian 2003.[7] For practicality, two methyl groups were placed at C-4 rather than phenyl substituents, and these corresponding compounds are named with an "**M**" appended. It is worth noting that an active space of (6,6) (MOs 35−42) proved possible by inspection of the MOs weighted appreciably in each reaction step. Thus, although a total of eight electrons is involved throughout the entire reaction sequence (C1═O7 and C2═C3 are lost, C1═C2 is formed, and C3−C4 is broken, as is C1−N6), no more than six electrons are redistributed at any one stage of the reaction. The validity was confirmed by inspection of the bond weightings using the Weinhold[8] NBO analysis as well as by a natural orbital analysis of each species. Smooth convergence resulted in all cases.

(7) Frisch, M. J.; et al. *Gaussian 03*, Revision C. 02; Gaussian, Inc.: Wallingford, CT, 2004.
(8) Weinhold, F. Natural Bond Orbital Methods. In *Encyclopedia of Computational Chemistry*; Schleyer, P. v. R., Ed.; Wiley: New York, 1998; Vol. 3, p 1792.

Table 1. Computational Results

entry	molecular species	energy, hartrees	energy, kcal[a]
	S0 Species		
1	conical intersection **A**	−439.68533	132.57
2	S0 geometry-optimized parent heterocycle	−439.89660	0.00
3	S0 with geometry of optimized S1, parent heterocycle	−439.88467	7.48
4	S0 with S1 transition-state geometry	−439.81295	52.49
5	conical intersection **B**	−439.72588	107.13
6	product pair S0 geometry optimized	−439.82941	42.16
	S1 Species		
7	conical intersection **A**, S1 surface	−439.68829	130.71
8	S1 with geometry of optimized S0 of the parent heterocycle	−439.72236	109.33
9	S1 optimized S1, parent heterocycle	−439.75189	90.81
10	S1 transition-state geometry	−439.70678	119.11
11	conical intersection **B**, S1 surface	−439.72588	107.13
12	product S1 with S0 optimized geometry	−439.49641	251.12
	Further Conical Intersections		
13	conical intersection **C**	−439.70940	117.57
14	conical intersection **D**	−439.67042	141.93
	Relaxed Conicals **B**, **C**, and **D** as S0 (B3LYP)		
15	relaxed conical **B**	−442.57828	
16	relaxed conical **C**	−442.65740	
17	relaxed conical **D**	−442.57790	
	Relaxed Conical **B** (CASSCF S0 − Local Minimum)		
18	relaxed conical **B** (local minimum)	−439.8990	

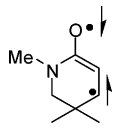
[a] Energies in kcal/mol are relative to reactant ground state (S0).

For the present, we merely outline the computations done and our reasoning. The conclusions derived are detailed below in the Discussion section. Details are included in the Supporting Information.

The first item was geometry optimization of the ground state, S0, of the reactant heterocycle **1M** (entry 2 in Table 1). We then obtained the Franck−Condon S1 excited state (entry 8 in Table 1), with an energy 109.34 kcal/mol above the S0 ground state.

We next wanted the relaxed singlet S1. We note that CAS S1 optimizations often prove difficult. Thus, a unique approach involving "state averaging" was used, with the ratio of S1 to S0 being increased incrementally from 1:1 until S1 was reached (Table 1, entry 9), giving an 18.53 kcal/mol relaxation energy. Interestingly, the S1 structure was similar in geometry to that of the ground state S0, with bond lengths being somewhat perturbed but bond 1−6 twisted by 15°.

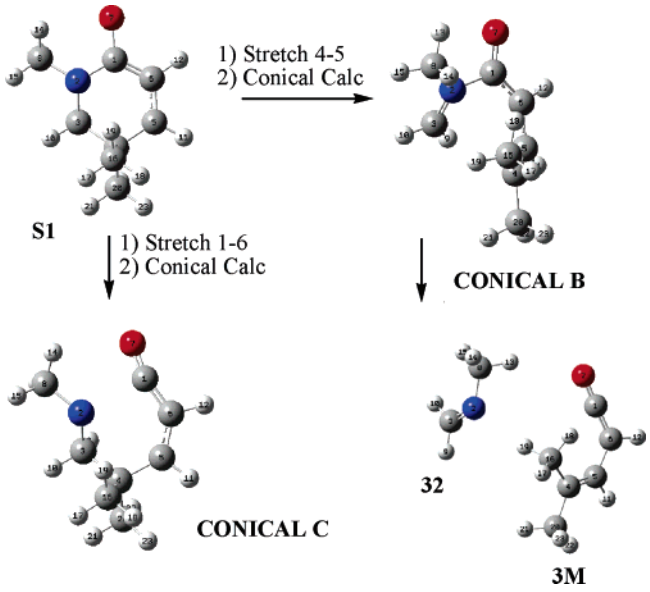
Having the S1 excited-state wavefunction in hand, we looked for evidence of weakening of bonds 1−6 and/or 4−5. For this, the NBO[8] analysis was employed with an NHO (hybrid orbital) basis set. However, the electron density in the two bonds of interest was normal and similar to those of the other molecular bonds, but the system had developed a 1−2 π-bond, and lone pairs were found at C-3 and the oxygen π-orbital. The NBO analysis revealed the excited state **1M*** to be $\pi-\pi^*$.



1M*

We turned next to searching for conical intersections starting with the excited singlet (i.e., S1) geometry. This led to a species, conical **A** (entry 1 in Table 1), whose geometry was different from that of the S1 excited state itself, with bond 1−6 being

Scheme 5. The Role of Conical Intersections

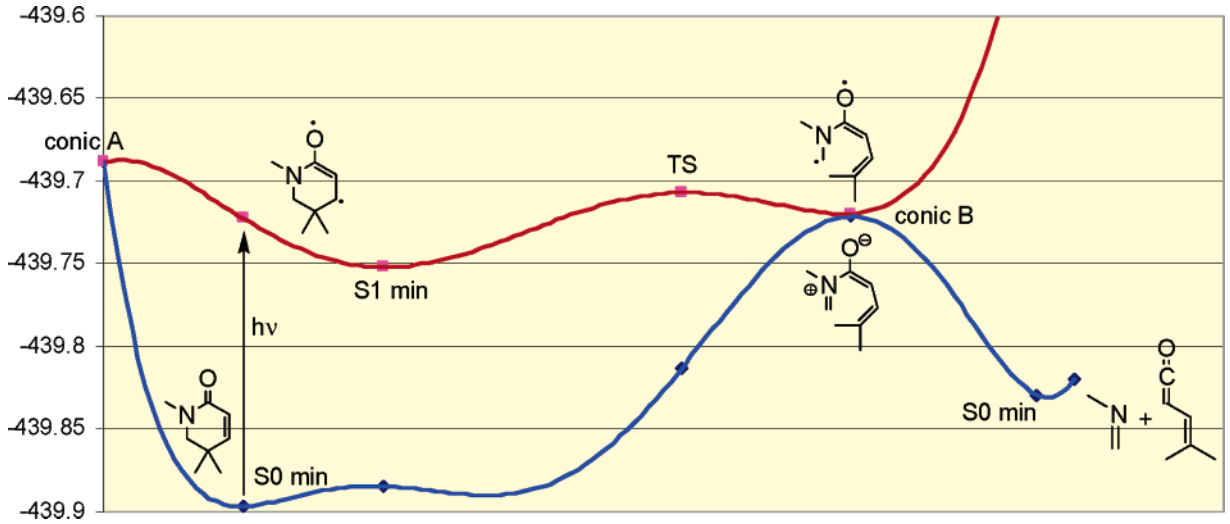


further twisted by an additional 65° but, again, no indication of weakening of bonds 1−6 and/or 4−5.

Hence, we proceeded to try stretching the two bonds, separately and together, prior to further computation. On stretching bond 4−5 of S1 to 1.8 Å and doing a conical optimization, the geometry returned the same conical intersection **A**. However, on further stretching, to 2.0 Å, a new conical intersection was found with a severed bond 4−5 and an energy of −439.7259 hartrees (107.13 kcal/mol above S0). This is termed conical intersection **B** (entries 5 and 11 in Table 1), which can lead to product or revert to reactant ground state (vide infra; see Scheme 5).

A third approach involved stretching bond 1−6 of S1 to 1.8 Å. Computation then led to a new conical intersection with bond 1−6 severed. This we termed conical intersection **C** (−439.7094

Scheme 6. Reaction Hypersurface



hartrees, 117.47 kcal/mol above S0, entry 13 in Table 1; see Scheme 5 again).

A fourth computation began with both bonds 1−6 and 4−5 stretched to 1.8 Å. Interestingly, only bond 4−5 remained severed, while bond 1−6 collapsed to give conical intersection **D** (Table 1, entry 14, 141.93 kcal/mol above S0). Thus, a cluster of conical intersections—**A**, **B**, **C**, and **D**—had been encountered, depending on the initial molecular deformation. This is summarized structurally in Scheme 5.

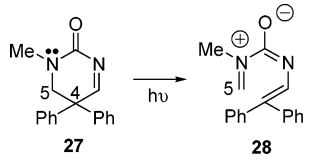
Next, it was of considerable interest to consider the S0 surface for molecular geometries corresponding to the four conical intersections **A**, **B**, **C**, and **D**. This promised to lead to an understanding of the fate of molecules utilizing these conical intersections. Ground-state S0 geometry optimization starting with conformation **C** returned the geometry to that of the ground-state heterocycle **1M**. Dramatically, parallel ground-state (i.e., S0) geometry optimization of structures **B** and **D** led the molecule to completely fragment to species **3M** and **32M**, in accord with experiment and the mechanistic interpretation in Scheme 7 (below). Often, geometry optimization of unstable species with an S0 configuration leads to an experimentally observed product. This then permits us to consider a hypersurface, as depicted in Scheme 6.

In order to obtain a better understanding of the reaction mechanism, we proceeded to a QST2 computation of the S1 reaction surface, beginning with **1M* (S1)** and proceeding onward to conical intersection **B**. To our knowledge, QST2 computations have hitherto been limited to ground-state surfaces. With the geometry-optimized reactant **S1** and conical intersection **B** as end points, an energy maximum (**TS**) was found, interposed with a 28 kcal/mol activation energy from the minimum **S1**. It is seen that vertical excitation of reactant **1M** (**S0**) leads to **S1** near a conical intersection (conic **A**), 39.91 kcal/mol above the **S1** minimum, and 21.38 kcal/mol above the Franck−Condon **S1**. Passage of **S1** via the 28 kcal/mol **TS** leads to conical intersection **B**, which leads, via **S0**, to two of the main initial photoproducts, ketene **3M** and imine **32M**. Scheme 6 thus shows a cross section of the hypersurfaces. However, one species was still lacking, namely zwitterion **31M**. Extensive S0 computations with the geometry of conical intersection **B** as a starting point but with a minimum geometry step size led to zwitterion **31M** as a local minimum, with bond 1−2 still intact (entry 18 in Table 1). With more common and larger step sizes in geometry optimization of conical intersection **B**, complete fragmentation resulted, as noted above. It is this species, **31M**, which undergoes nucleophilic attack by methanol and by cyanide anion.

Discussion. We see that our original report on the effect of stabilization of odd-electron density on carbon-5, leading to scission of bond 4−5 of cyclohexenones, has proven a more general phenomenon than originally thought. In the early work, this stabilization was invariably achieved by virtue of phenyl substitution. However, we now see that a ring nitrogen operates in the same fashion.

Interestingly, in research by Canovas,[5c] ring-opening of dihydropyridones with fission of bond 4−5 had been encountered but was ascribed to an electrocyclic process. In that research, there was some evidence for ketene formation, which was described as not subject to a mechanistic rationale.

Very recently, we have observed still another example of 4−5 bond fission[6] (see eq 2). The commonality of fission of bond

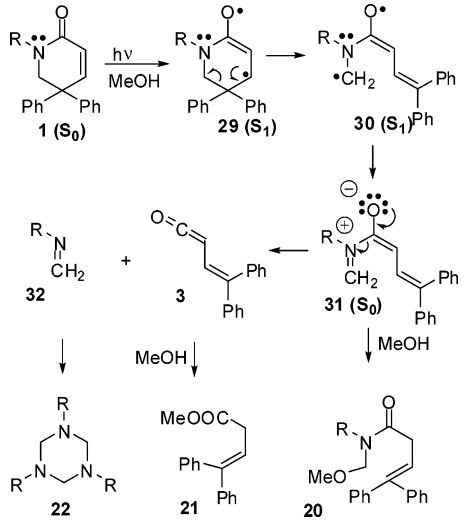


27 **28** (2)

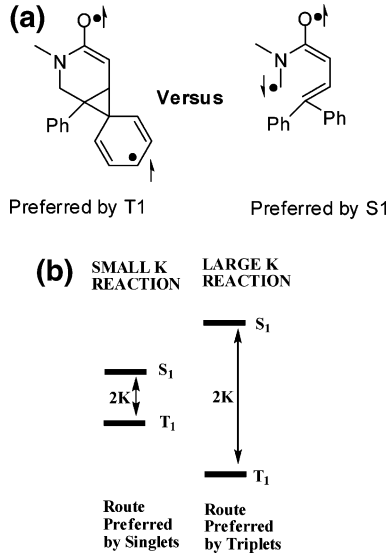
4−5 is striking. The evidence suggests that the initial step is generally cleavage of this bond. This clearly is involved in the route to product **20**. Scheme 7 suggests that scission of bond 1−6, leading to ketene **3** and imine **32**, occurs only after the initial 4−5 fission via zwitterion **31**. However, to some extent, loss of bonds 1−6 and 4−5 may occur concertedly. Thus, conical intersection **B** funnels to a critical point on the ground-state surface. As noted in Scheme 6, that surface leads to fragmentation to afford the ketene **3M** and the imine **32M**. Analogously, stretching of bond 1−6 leads to the conical intersection **C**, which provides another route to the ground-state surface. In this case, S0 electronics leads the molecule back to reactant **1M**.

Turning now to the triplet photochemistry, we note that the reaction affording **23a** (cf. Scheme 4) is basically a Type B process, occurring by bridging of a C-4 phenyl group. The triplet

Scheme 7. Reaction Mechanisms



Scheme 8. Singlet−Triplet Reactivity Differences



vs singlet reactivity is understood in terms of the large *K*−small *K* (exchange integral) concept[9] (Scheme 8). With an energy separation of 2 K between S1 and T1, large-*K* species are preferred by the triplet, while the small-*K* species are preferred by the singlet. The Type B process of Scheme 1 does lead to a first intermediate with diradical character and odd-electron densities; in contrast, the ring fragmentation process has zwitterionic character (Scheme 8a).

In conclusion, we see that there is a cooperative parallelism between electron-pushing mechanistic treatment of photochemical reactions and an ab initio computational treatment. A most interesting point in the present study is that the energy barriers between the Franck−Condon excited state and the point where the molecule reaches ground-state product would not have been observed without the search for conical intersections.

(9) (a) Zimmerman, H. E.; Armesto, D.; Amezua, M. G.; Gannett, T. P.; Johnson, R. P. *J. Am. Chem. Soc.* **1979**, *101*, 6367−6383. (b) Zimmerman, H. E.; Factor, R. E. *Tetrahedron* **1981**, *37*, Suppl. 1, 125−141. (c) Zimmerman, H. E.; Penn, J. H.; Johnson, M. R. *Proc. Natl. Acad. Sci. U.S.A.* **1981**, *78*, 2021−2025. (d) The present situation is in accord with the previously published examples.

Experimental Section

General Procedures. Melting points were determined in open capillaries and are uncorrected. Column chromatography was performed on silica gel (60−80 mesh) mixed with 1% of a Sylvania 2282 green phosphor and slurry-packed into quartz columns to allow monitoring of zones with a hand-held UV lamp. ^{1}H and ^{13}C NMR spectra were recorded at 300 and 75.4 MHz, respectively, with TMS as an internal standard; ^{31}P NMR sprectra were recorded at 121.4 MHz with 85% H_3PO_4 as an external standard. Photolysis experiments were carried out with a 400-W medium-pressure mercury lamp in a quartz immersion well with 0.2 M copper sulfate filter solution.

2-Chloro-*N*-(3-hydroxy-2,2-diphenylpropyl)acetamide (14). A solution of 0.30 mL (3.77 mmol) of chloroacetyl chloride in 5.0 mL of dichloromethane was added dropwise to a stirred solution of 855 mg (3.77 mmol) of amino alcohol **13**[10] and 0.55 mL (3.9 mmol) of triethylamine in 10 mL of dichloromethane at −10 to −5 °C. The mixture was stirred for 4 h, quenched with water, extracted with dichloromethane, washed with diluted HCl and brine, dried, concentrated in vacuo, and treated with ether to give 0.895 g (78%) of the crystalline 2-chloro-*N*-(3-hydroxy-2,2-diphenylpropyl)acetamide (**14**), mp 128−129 °C, after filtration and recrystallization from ethyl acetate. ^{1}H NMR ($CDCl_3$, 300 MHz): δ 7.17−7.37 (m, 10H), 6.69 (t, broad, 1H), 4.18 (d, J = 6.3 Hz, 2H), 4.15 (d, J = 6.3 Hz, 2H), 4.00 (s, 2H), 2.72 (t, J = 6.3 Hz, 1H). ^{13}C NMR ($CDCl_3$, 75.4 MHz): δ 167.21, 143.47, 128.80, 127.97, 127.18, 67.26, 52.25, 45.50, 42.64. HRMS: calcd for $C_{17}H_{18}ClNO_2$, 326.0926 (M + Na); found, 326.0913 (M + Na).

2-Chloro-*N*-(2-formyl-2,2-diphenylethyl)acetamide (15). To a solution of 2.5 mL (28.7 mmol) of oxalyl chloride in 50 mL of dichloromethane at −70 °C under nitrogen was added 2.7 mL (38 mmol) of DMSO. The mixture was stirred for 15 min, and then 5.69 g (18.7 mmol) of amido alcohol **14** in 60 mL of dichloromethane was added. The mixture was stirred at −70 °C for 20 min and treated with 10.5 mL (75.3 mmol) of triethylamine. The mixture was allowed to warm to room temperature, washed with water, dried, and concentrated in vacuo to give the product **15** in literally quantitative yield as a thick oil which slowly crystallized; mp 64−65 °C. ^{1}H NMR ($CDCl_3$, 300 MHz): δ 9.89 (s, 1H), 7.33−7.44 (m, 6H), 7.17−7.21 (m, 4H), 6.83 (t, broad, 1H), 4.23 (d, J = 6.0 Hz, 2H), 3.84 (s, 2H). ^{13}C NMR ($CDCl_3$, 75.4 MHz): δ 199.04, 165.62, 137.83, 129.30, 128.87, 128.33, 64.08, 42.85, 42.61. HRMS: calcd for $C_{17}H_{16}ClNO_2$, 324.0767 (M + Na); found, 324.0775 (M + Na).

Diethyl (2-Formyl-2,2-diphenylethylcarbamoyl)methylphosphonate (16). A mixture of 0.81 g (2.7 mmol) of formylamide **15**, 0.50 mL (2.9 mmol) of triethylphosphite, and 0.403 g (2.7 mmol) of sodium iodide was refluxed in 20 mL of acetonitrile for 6 h, diluted with water, extracted with ether, washed with brine, dried, concentrated in vacuo, and subjected to chromatography on a silica gel column (12.0 cm × 2.5 cm, eluent hexane/ethyl acetate 3:1, then ethyl acetate). Fraction 2 gave 0.643 g (59%) of the product **16** as an oil. ^{1}H NMR ($CDCl_3$, 300 MHz): δ 9.90 (s, 1H), 7.30−7.42 (m, 6H), 7.19−7.23 (m, 4H), 6.82 (t, J = 5.4 Hz, 1H), 4.22 (d, J = 5.7 Hz, 2H), 4.01 (dq, J_1 = 7.2 Hz, J_2 = 7.2 Hz, 4H), 2.69 (d, J = 20.4 Hz, 2H), 1.25 (t, J = 7.2 Hz, 6H). ^{13}C NMR ($CDCl_3$, 75.4 MHz): δ 198.93, 164.02, 163.97, 138.08, 129.18, 128.89, 128.07, 63.83, 62.76, 62.68, 43.24, 36.05, 34.31, 16.41, 16.34. ^{31}P NMR ($CDCl_3$, 121.4 MHz): δ 22.73. HRMS: calcd for $C_{21}H_{26}NO_5P$, 404.1627 (M + H); found, 404.1617 (M + H).

5,6-Dihydro-5,5-diphenylpyridin-2(1*H*)-one (17). A solution of 634 mg (1.57 mmol) of the phosphonate **16** in 5.0 mL of methanol was added to a solution of sodium methoxide (from 72 mg (3.14 mmol) of sodium in 10 mL of methanol), and the mixture was stirred overnight at ambient temperature. The solvent was evaporated in vacuo, and the residue was treated with water, extracted with benzene, washed, dried, concentrated in vacuo, and subjected to chromatography on a silica

(10) Meschino, J. A.; Bond, C. H. *J. Org. Chem.* **1963**, *28*, 3129−3134.

gel column (4.0 cm × 2.5 cm, eluent hexane/ethyl acetate 1:2) to afford 238 mg (61%) of product **17**; mp 166−167 °C after recrystallization from butyl ether. ^{1}H NMR ($CDCl_3$, 300 MHz): δ 7.20−7.36 (m, 10H), 7.10 (d, J = 10.2 Hz, 1H), 6.08 (dd, J_1 = 10.2 Hz, J_2 = 2.0 Hz, 1H), 5.82 (s broad, 1H), 3.97 (d, J = 2.4 Hz, 2H). ^{13}C NMR ($CDCl_3$, 75.4 MHz): δ 165.94, 148.86, 144.32, 128.76, 127.67, 127.27, 123.94, 51.11, 48.39. HRMS: calcd for $C_{15}H_{17}NO$, 250.1232 (M + H); found, 250.1239 (M + H).

Alkylation of 5,6-Dihydro-5,5-diphenylpyridin-2(1*H*)-one (17): General Procedure. A 71 mg (1.77 mmol) portion of sodium hydride (60% in mineral oil) was washed free of oil with hexane and suspended in 5.0 mL of DMF, and then 400 mg (1.61 mmol) of lactam **17** in 10 mL of DMF was added with external ice cooling and stirring. After the evolution of hydrogen was complete, the appropriate halide (1.7 mmol) was added and the stirring continued overnight. The mixture was diluted with water, extracted with benzene, washed, dried, concentrated in vacuo, and subjected to chromatography or crystallization to afford one of the following:

5,6-Dihydro-1-methyl-5,5-diphenylpyridin-2(1*H*)-one (1a). Yield: 361 mg (82%); mp 121−122 °C after recrystallization from heptane. ^{1}H NMR ($CDCl_3$, 300 MHz): δ 7.24−7.35 (m, 6H), 7.15−7.18 (m, 4H), 7.00 (d, J = 9.9 Hz, 1H), 6.07 (d, J = 9.9 Hz, 1H), 3.89 (s, 2H), 3.04 (s, 3H). ^{13}C NMR ($CDCl_3$, 75.4 MHz): δ 164.12, 146.52, 144.39, 128.78, 127.47, 127.28, 124.48, 58.92, 49.09, 34.37. HRMS: calcd for $C_{18}H_{17}NO$, 264.1388 (M + H); found, 264.1392 (M + H).

1-(4-*tert*-Butylbenzyl)-5,6-dihydro-5,5-diphenylpyridin-2(1*H*)-one (1b). Yield: 577 mg (91%); mp 162−163.5 °C after recrystallization from isopropanol. ^{1}H NMR ($CDCl_3$, 300 MHz): δ 7.19−7.29 (m, 8H), 7.01−7.12 (m, 6H), 6.97 (d, J = 9.7 Hz, 1H), 6.17 (d, J = 9.7 Hz, 1H), 4.59 (s, 2H), 3.82 (s, 2H), 1.32 (s, 9H). ^{13}C NMR ($CDCl_3$, 75.4 MHz): δ 163.88, 150.58, 146.70, 144.278, 133.54, 128.69, 128.66, 127.62, 127.18, 125.66, 124.82, 56.05, 49.76, 48.96, 34.69, 31.56. HRMS: calcd for $C_{28}H_{29}NO$, 418.2147 (M + Na); found, 418.2131 (M + Na).

Methyl 5,6-Dihydro-2-oxo-5,5-diphenylpyridine-1(2*H*)-carboxylate (1c). Chromatography (10.0 cm × 2.5 cm column, eluent hexane/ethyl acetate 3:1) afforded 256 mg (64%) of the starting material (fraction 2) and 143 mg (29%) of the product (fraction 1); mp 140.5−142 °C after recrystallization from benzene/heptane. ^{1}H NMR ($CDCl_3$, 300 MHz): δ 7.27−7.36 (m, 7H), 7.16−7.18 (m, 4H), 6.16 (d, J = 9.9 Hz, 1H), 4.47 (d, J = 0.9 Hz, 2H), 3.88 (s, 3H). ^{13}C NMR ($CDCl_3$, 75.4 MHz): δ 162.68, 154.77, 151.36, 142.82, 128.92, 127.51, 127.46, 124.95, 54.25, 53.94, 49.12. HRMS: calcd for $C_{19}H_{17}NO_3$, 330.1106 (M + Na); found, 330.1097 (M + Na).

Irradiation of 5,6-Dihydro-1-methyl-5,5-diphenylpyridin-2(1*H*)-one (1a) in Methanol. A solution of 400 mg (1.52 mmol) of heterocycle **1a** in 250 mL of methanol was first purged with nitrogen for 1 h. Irradiation was then carried out in an enclosed box with a 0.2 M $CuSO_4$ filter solution for 2 h. TLC indicated three new spots and practically complete conversion of the starting material. The mixture was separated by chromatography (12.0 cm × 2.5 cm column, eluent hexane/ether 9:1, then hexane/ethyl acetate 3:1, 1:1) to give the following products:

Fraction 1: Methyl 4,4-Diphenylbut-3-enoate (21).[11] Yield: 129 mg (34%) as an oil. ^{1}H NMR ($CDCl_3$, 300 MHz): δ 7.17−7.41 (m, 10H), 6.25 (t, J = 7.4 Hz, 1H), 3.70 (s, 3H), 3.17 (d, J = 7.4 Hz, 2H). ^{13}C NMR ($CDCl_3$, 75.4 MHz): δ 172.48, 144.95, 142.12, 139.41, 129.95, 128.58, 128.33, 127.62, 120.50, 52.06, 35.46.

Fraction 2: *N*-(Methoxymethyl)-*N*-methyl-4,4-diphenylbut-3-enamide (20a). Yield: 142 mg (38%) as an oil, mixture of isomers. ^{1}H NMR ($CDCl_3$, 300 MHz): δ 7.19−7.42 (m, 10H), 6.32, 6.33 (2t, J = 7.4 Hz, 1H), 4.45, 4.80 (2s, 2H), 3.09, 3.28 (2s, 3H), 3.22, 3.28 (2d, J = 7.0 Hz, 2H), 2.85, 2.98 (2s, 3H). ^{13}C NMR ($CDCl_3$, 75.4 MHz): δ 172.52, 172.08, 144.18, 143.79, 141.76, 141.70, 139.36, 139.30, 129.65, 129.58, 128.23, 128.15, 128.05, 127.95, 127.58, 127.26, 125.90, 125.46, 121.71, 121.25, 80.98, 77.63, 55.65, 54.88, 34.89, 34.49, 33.49, 33.41. HRMS: calcd for $C_{19}H_{21}NO_2$, 318.1470 (M + Na); found, 318.1456 (M + Na).

Fraction 3: *N*-Methyl-4,4-diphenylbut-3-enamide. A product of hydrolysis of *N*-(methoxymethyl)-*N*-methyl-4,4-diphenylbut-3-enamide on the column. Yield: 80 mg (6%); mp 128−129 °C. ^{1}H NMR ($CDCl_3$, 300 MHz): δ 7.15−7.42 (m, 10H), 6.26 (t, J = 7.7 Hz, 1H), 5.56 (broad, 1H), 3.05 (d, J = 7.7 Hz, 2H), 2.80 (d, J = 4.8 Hz, 3H). ^{13}C NMR ($CDCl_3$, 75.4 MHz): δ 171.71, 145.55, 141.88, 139.23, 129.79, 128.61, 128.34, 127.69, 127.66, 127.52, 121.29, 37.75, 26.57. HRMS: calcd for $C_{17}H_{17}NO$, 252.1388 (M + H); found, 252.1387 (M + H).

Irradiation of 5,6-Dihydro-1-methyl-5,5-diphenylpyridin-2(1*H*)-one (1a) in *tert*-Butanol. A solution of 400 mg (1.52 mmol) of heterocycle **1a** in 250 mL of *tert*-butanol was purged with nitrogen for 1 h. Irradiation was carried out in an enclosed box with a 0.2 M $CuSO_4$ filter solution for 2 h. TLC indicated three new spots and practically complete conversion of the starting material. The mixture was separated by chromatography (12.0 cm × 2.5 cm column, eluent hexane/ether 9:1, then hexane/ethyl acetate 3:1, 1:1) to give the following products:

Fraction 1: *tert*-Butyl 4,4-Diphenylbut-3-enoate (25).[12] Yield: 121 mg (27%); mp 109−110 °C after recrystallization from hexane. ^{1}H NMR ($CDCl_3$, 300 MHz): δ 7.17−7.40 (m, 10H), 6.24 (t, J = 7.3 Hz, 1H), 3.07 (d, J = 7.3 Hz, 2H), 1.45 (s, 9H). ^{13}C NMR ($CDCl_3$, 75.4 MHz): δ 171.39, 144.46, 142.36, 139.64, 130.07, 128.49, 128.30, 127.67, 127.49, 121.38, 80.91, 36.87, 28.31.

Fraction 2: *N*-(*tert*-Butoxymethyl)-*N*-methyl-4,4-diphenylbut-3-enamide (24). Yield: 110 mg (21.5%) as an oil, mixture of isomers. ^{1}H NMR ($CDCl_3$, 300 MHz): δ 7.18−7.40 (m, 10H), 6.32, 6.37 (2t, J = 7.5 Hz, 1H), 4.47, 4.87 (2s, 2H), 3.16, 3.28 (2d, J = 7.5 Hz, 2H), 2.84, 2.96 (2s, 3H), 1.08, 1.23 (2s, 9H). ^{13}C NMR ($CDCl_3$, 75.4 MHz): δ 172.39, 171.50, 144.25, 143.68, 142.21, 142.17, 139.81, 139.73, 130.02, 129.94, 128.51, 128.41, 128.39, 128.20, 127.99, 127.60, 127.58, 127.50, 127.43, 127.34, 122.54, 121.79, 74.11, 73.76, 72.92, 70.66, 35.41, 34.55, 33.65, 33.32, 28.11, 27.70. HRMS: calcd for $C_{22}H_{27}NO_2$, 360.1939 (M + Na); found, 360.1949 (M + Na).

Fraction 3: *N*-Methyl-4,4-diphenylbut-3-enamide. A product of hydrolysis of *N*-(*tert*-butoxymethyl)-*N*-methyl-4,4-diphenylbut-3-enamide on the column. Yield: 64 mg (16.7%); mp 128−129 °C. ^{1}H NMR ($CDCl_3$, 300 MHz): δ 7.15−7.42 (m, 10H), 6.26 (t, J = 7.7 Hz, 1H), 5.56 (broad, 1H), 3.05 (d, J = 7.7 Hz, 2H), 2.80 (d, J = 4.8 Hz, 3H).

Irradiation of 5,6-Dihydro-1-methyl-5,5-diphenylpyridin-2(1*H*)-one (1a) in Methanol in the Presence of Potassium Cyanide. Potassium cyanide (10.0 g) was stirred in 250 mL of methanol for 15 min and the solution filtered. To this solution was added 200 mg (0.76 mmol) of heterocycle **1a**, and the solution was purged with nitrogen for 1 h. Irradiation was carried out in an enclosed box with a 0.2 M $CuSO_4$ filter solution for 20 min. TLC showed no starting material left. The resulting solution was concentrated in vacuo, diluted with water, and extracted with benzene. The organic layer was separated, washed with brine, dried, concentrated in vacuo, and subjected to column chromatography (15.0 cm × 2.5 cm column, eluent dichloromethane/ethyl acetate 19:1) to give the following products:

Fraction 1: Methyl 4,4-Diphenylbut-3-enoate (21). Yield: 6.8 mg (3.5%).

Fraction 2: *N*-(Methoxymethyl)-*N*-methyl-4,4-diphenylbut-3-enamide (20a). Yield: 8.1 mg (3.6%).

Fraction 3: *N*-(Cyanomethyl)-*N*-methyl-4,4-diphenylbut-3-enamide (4). Yield: 31.5 mg (14.3%) as an oil. ^{1}H NMR ($CDCl_3$, 300 MHz): δ 7.16−7.43 (m, 10H), 6.27 (t, J = 7.2 Hz, 1H), 4.33 (s, 2H), 3.21 (d, J = 7.2 Hz, 2H), 2.95 (s, 3H). ^{13}C NMR ($CDCl_3$, 75.4 MHz):

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(12) Wong, J.-W.; Natalie, K. J., Jr.; Nwokogu, G. C.; Pisipati, J. S.; Flaherty, P. T.; Greenwood, T. D.; Wolfe, J. F. *J. Org. Chem.* **1997**, *62*, 6152−6159.

δ 171.76, 145.11, 141.83, 139.47, 129.85, 128.71, 128.36, 127.78, 127.73, 127.61, 120.56, 115.43, 35.44, 35.40, 34.55. HRMS: calcd for $C_{19}H_{18}N_2O$, 893.4155 (3M + Na); found, 843.4119 (3M + Na).

Fraction 4: Methyl 2-(*N*-Methyl-4,4-diphenylbut-3-enamido)-acetate (24). Yield: 79.3 mg (32.3%) as an oil; mixture of cis and trans isomers. ^{1}H NMR ($CDCl_3$, 300 MHz): δ 7.15−7.43 (m, 10H), 6.26, 6.32 (2t, J = 7.2 Hz, 1H), 3.84, 4.12 (2s, 2H), 3.62, 3.74 (2s, 3H), 3.14, 3.25 (2d, J = 7.2 Hz, 2H), 2.92, 2.97 (2s, 3H). ^{13}C NMR ($CDCl_3$, 75.4 MHz): δ 172.16, 171.73, 169.88, 169.47, 144.34, 144.20, 142.14, 141.77, 139.66, 139.33, 129.94, 128.94, 128.77, 128.54, 128.42, 128.23, 127.97, 127.90, 127.62, 127.54, 127.44, 121.66, 121.61, 52.43, 52.24, 51.44, 49.55, 36.66, 35.51, 35.12, 34.75. HRMS: calcd for $C_{20}H_{21}NO_3$, 669.2941 (2M + Na); found, 669.2947 (2M + Na).

Irradiation of 5,6-Dihydro-1-methyl-5,5-diphenylpyridin-2-one (1a) in *tert*-Butanol with Acetophenone as a Sensitizer. A solution of 200 mg (0.76 mmol) of 5,6-dihydro-1-methyl-5,5-diphenylpyridin-2-one (**1a**) and 1.8 mL (20 equiv) of acetophenone in 250 mL of *tert*-butanol was purged with nitrogen for 1 h. Irradiation was then carried out in an enclosed box with a 0.2 M $CuSO_4$ filter solution for 20 min. TLC showed no starting material left. The resulting solution was concentrated in vacuo, and most of the acetophenone was removed in vacuum with an oil pump. The residue was separated by column chromatography (10.0 cm × 2.5 cm column, eluent hexane/ethyl acetate 3:1) to afford *endo*-3-methyl-5,6-diphenyl-3-azabicyclo[3.1.0]hexan-2-one (**23a**); 171 mg (85.5%) as a viscous oil. ^{1}H NMR ($CDCl_3$, 300 MHz): δ 7.26−7.43 (m, 10H), 3.66 (d, J = 10.8 Hz, 1H), 3.26 (dd, J = 10.8 Hz, J = 1.7 Hz, 1H), 2.87 (d, J = 8.7 Hz, 1H), 2.73 (dd, J = 8.7 Hz, J = 1.7 Hz, 1H), 2.33 (s, 3H). ^{13}C NMR ($CDCl_3$, 75.4 MHz): δ 172.12, 140.54, 133.68, 129.45, 129.06, 128.70, 127.51, 127.47, 127.41, 53.19, 33.52, 33.43, 33.11, 28.49. HRMS: calcd for $C_{18}H_{17}NO$, 549.2518 (2M + Na); found, 549.2515 (2M + Na). The structure was confirmed by basic hydrolysis and methylation of methyl *endo*-4-oxo-1,6-diphenyl-3-azabicyclo[3.1.0]hexane-3-carboxylate (**23c**) to give an identical sample of *endo*-3-methyl-5,6-diphenyl-3-azabicyclo-[3.1.0]hexan-2-one (**23a**).

Irradiation of Methyl 5,6-Dihydro-2-oxo-5,5-diphenylpyridine-1(2*H*)-carboxylate (1c) in Benzene. A solution of 400 mg (1.52 mmol) of heterocycle **1c** in 250 mL of benzene was purged with nitrogen for 1 h. Irradiation was then carried out in an enclosed box with a 0.2 M $CuSO_4$ filter solution for 20 min. The NMR spectrum showed the formation of only one new product with ca. 40% conversion. The irradiation was then continued for a total of 90 min. Concentration in vacuo and chromatography (10.0 cm × 2.5 cm column, eluent hexane/ethyl acetate 3:1) afforded methyl *endo*-4-oxo-1,6-diphenyl-3-azabicyclo-[3.1.0]hexane-3-carboxylate **(23c)**, 359 mg (89.3%); mp 137−138.5 °C after recrystallization from isopropanol. ^{1}H NMR ($CDCl_3$, 300 MHz): δ 7.26−7.45 (m, 10H), 4.00 (d, J = 11.7 Hz, 1H), 3.90 (dd, J = 11.7 Hz, J = 1.2 Hz, 1H), 3.62 (s, 3H), 3.03 (d, J = 9.0 Hz, 1H), 2.84 (dd, J = 9.0 Hz, J = 1.2 Hz, 1H). ^{13}C NMR ($CDCl_3$, 75.4 MHz): δ 171.29, 151.23, 139.27, 132.41, 129.28, 129.25, 129.08, 128.00, 127.93, 127.55, 53.52, 49.94, 34.18, 34.00, 33.30. HRMS: calcd for $C_{18}H_{17}NO_3$, 637.2315 (2M + Na); found, 637.2329 (2M + Na).

Irradiation of Methyl 5,6-Dihydro-2-oxo-5,5-diphenylpyridine-1(2*H*)-carboxylate (1c) in Methanol. A solution of 200 mg (0.65 mmol) of heterocycle **1c** in 250 mL of methanol was purged with nitrogen for 1 h. Irradiation was then carried out in an enclosed box with a 0.2 M $CuSO_4$ filter solution for 40 min. The mixture was chromatographed (12.0 cm × 2.5 cm column, eluent hexane/ethyl acetate 7:1, then 4:1 and 2:1) to give the following products:

Fraction 1: Methyl 4,4-Diphenylbut-3-enoate (21). Yield: 11.3 mg (8%).

Fraction 2: Methyl 4,4-Diphenylbut-3-enoylmethoxymethylcarbamate (20c). Yield: 16.4 mg (9%) as an oil; one isomer. ^{1}H NMR ($CDCl_3$, 300 MHz): δ 7.17−7.41 (m, 10H), 6.32 (t, J = 6.9 Hz, 1H), 5.16 (s, 2H), 3.80 (s, 3H), 3.76 (d, J = 6.9 Hz, 2H), 3.37 (s, 3H). ^{13}C NMR ($CDCl_3$, 75.4 MHz): δ 174.69, 154.72, 144.80, 142.41, 139.58, 130.01, 128.52, 128.29, 127.74, 127.57, 127.51, 121.31, 75.26, 57.46, 54.11, 39.20. HRMS: calcd for $C_{20}H_{21}NO_4$, 701.2833 (2M + Na); found, 701.2827 (2M + Na).

Fraction 3: The starting material. Yield: 27.2 mg.

Fraction 4: Methyl *endo*-4-oxo-1,6-diphenyl-3-azabicyclo[3.1.0]-hexane-3-carboxylate (23c). Yield: 63.5 mg (36.7).

Irradiation of 1-(4-*tert*-Butylbenzyl)-5,6-dihydro-5,5-diphenylpyridin-2(1*H*)-one (1b) in Methanol. A solution of 350 mg (0.89 mmol) of heterocycle **1b** in 250 mL of methanol was purged with nitrogen for 1 h. The irradiation was then carried out in an enclosed box with a 0.2 M $CuSO_4$ filter solution for 20 min. NMR indicated essentially complete conversion of the starting material. Chromatography (12.0 cm × 2.5 cm column, eluent hexane/ethyl acetate 9:1, 7:1, 5:1, then dichloromethane/ethyl acetate 29:1) gave the following products:

Fraction 1: Methyl 4,4-Diphenylbut-3-enoate (21). Yield: 120 mg (53.6%).

Fraction 2: 1,3,5-Tris(4-*tert*-butylbenzyl)-1,3,5-triazinane (22b). Yield: 46 mg (29.7%); mp 130.5−131.5 °C after recrystallization from isopropanol. ^{1}H NMR ($CDCl_3$, 300 MHz): δ 7.26 (q, J = 8.4 Hz, 12H), 3.64 (s, 6H), 3.42 (broad, 3H), 1.30 (s, 27H). ^{13}C NMR ($CDCl_3$, 75.4 MHz): δ 150.00, 135.69, 128.81, 125.26, 74.10, 56.91, 34.64, 31.62. HRMS: calcd for $C_{36}H_{51}N_3$, 526.4161 (M + H); found, 526.4176 (M + H).

Fraction 3: *N*-(4-*tert*-Butylbenzyl)-*N*-(methoxymethyl)-4,4-diphenylbut-3-enamide (20b). Yield: 81 mg (21.3%) as an oil; mixture of cis and trans isomers. ^{1}H NMR ($CDCl_3$, 300 MHz): δ 7.09−7.40 (m, 13H), 6.93 (d, J = 7.5 Hz, 1H), 6.32, 6.37 (2t, J = 7.5 Hz, 1H), 4.62, 4.85 (2s, 2H), 4.38 (s, 2H), 3.23, 3.33 (2d, J = 7.5 Hz, 2H), 3.05, 3.34 (2s, 3H), 1.30 (s, 9H). ^{13}C NMR ($CDCl_3$, 75.4 MHz): δ 173.31, 172.32, 150.59, 150.45, 144.39, 144.21, 142.07, 139.68, 139.62, 134.59, 133.61, 130.00, 129.89, 128.54, 128.27, 128.16, 128.07, 127.62, 127.57, 127.48, 126.32, 125.84, 125.70, 125.61, 125.41, 122.15, 121.81, 78.81, 76.28, 56.33, 55.25, 48.94, 48.06, 35.21, 34.95, 34.63, 31.51. HRMS: calcd for $C_{29}H_{33}NO_2$, 450.2409 (M + Na); found, 450.2428 (M + Na).

Fraction 4: *N*-(4-*tert*-Butylbenzyl)-4,4-diphenylbut-3-enamide. A product of hydrolysis of *N*-(4-*tert*-butylbenzyl)-*N*-(methoxymethyl)-4,4-diphenylbut-3-enamide on the column. Yield: 21 mg (16.7%). ^{1}H NMR ($CDCl_3$, 300 MHz): δ 7.12−7.38 (m, 14H), 6.29 (t, J = 7.8 Hz, 1H), 5.77 (broad, 1H), 4.40 (d, J = 5.7 Hz, 2H), 3.08 (d, J = 7.8 Hz, 2H), 1.31 (s, 9H). ^{13}C NMR ($CDCl_3$, 75.4 MHz): δ 170.85, 150.80, 145.85, 141.85, 139.27, 135.28, 129.84, 128.68, 128.40, 127.79, 127.73, 127.59, 125.85, 121.12, 43.60, 37.97, 34.72, 31.52. HRMS: calcd for $C_{27}H_{29}NO$, 406.2147 (M + Na); found, 406.2164 (M + Na).

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Supporting Information Available: Experimental procedures, NMR spectra, X-ray data (in CIF format), computational files, and complete ref 7. This material is available free of charge via the Internet at http://pubs.acs.org.

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