Studies on the Intramolecular Cycloaddition Reaction of Mesoionics Derived from the Rhodium(II)-Catalyzed Cyclization of Diazoimides

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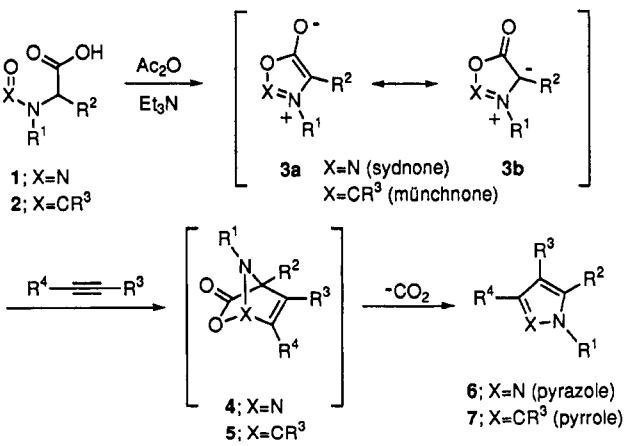
A series of alkenyl-substituted imides were prepared by treating the appropriate amide with 2,2,6-trimethyl-4*H*-1,3-dioxen-4-one in xylene at 140 °C to give the N-acetoacylated imides. Exposure of these imides to standard diazo transfer conditions gave the desired diazoimides. The carbenoid intermediate derived by treatment of the diazoimide with rhodium(II) acetate undergoes ready cyclization onto the neighboring amide carbonyl oxygen atom to generate an isomünchnone intermediate. Subsequent 1,3-dipolar cycloaddition across the pendant olefin affords the cycloadduct in high yield. The stereochemical assignment of several of the cycloadducts was deduced by X-ray crystallography. The stereochemical outcome of the reaction is the consequence of an *endo* cycloaddition of the neighboring π-bond across the transient isomünchnone dipole. Molecular mechanics calculations were used to model energy differences between the *endo* and *exo* diastereomers. The calculations reveal that the *endo* diastereomers are significantly (8–12 kcal/mol) lower in energy than the corresponding *exo* isomers thereby providing a rationale for the preferred *endo* cycloaddition. Ring opening of the cycloadducts occurred readily producing a transient *N*-acyliminium ion which either lost a proton to give an enamide or was reduced by Et_3SiH to afford a bicyclic piperidine ring.

Mesoionic compounds have been known for many years and have been extensively utilized as substrates in 1,3-dipolar cycloadditions.[1-7] The term *mesoionic* is generally restricted to five membered heterocycles that cannot be represented satisfactorily by normal covalent structures and are best described as a hybrid of all possible charged forms.[8,9] There are two general types of mesoionics (type A and B), each showing quite distinct chemical properties.[6] Embedded within the type A class are 1,3-dipoles that participate in dipolar cycloaddition reactions with various dipolarophiles. Type B mesoionics generally ring open to produce acyclic valence tautomers which then undergo further chemistry.[7] As a consequence of the "*masked*" dipole within the *type A* mesoionics, the structure, physical properties, and reactions of these compounds have drawn the most scrutiny.

Two of the most extensively studied members of the type A class of mesoionics are the 1,2,3-oxadiazolium-5-olates (sydnones)[8-13] and the 1,3-oxazolium-5-olates (münchnones).[14-16] The 1,3-dipoles embedded within these mesoionics correspond to an azomethine imine and an azomethine ylide, respectively. The cycloaddition chemistry of these systems has proven to be quite valuable in natural product synthesis and for the construction of novel heterocyclic systems.[7,14] The most extensively studied reaction of sydnones involves 1,3-dipolar cycloaddition with acetylenic dipolarophiles to produce substituted pyrazoles **6** by extrusion of carbon dioxide from the initially formed cycloadduct **4**.[7] The reaction of münchnones with acetylenic dipolarophiles also represents a useful strategy for the formation of substituted pyrroles **7**.[7]



Whereas the chemistry of sydnones and münchnones has been studied in great detail, much less is known about the isomeric anhydro-4-hydroxy-1,3-oxazolium hydroxides (**9a,b**) (isomünchnones). Isomünchnones contain a car-

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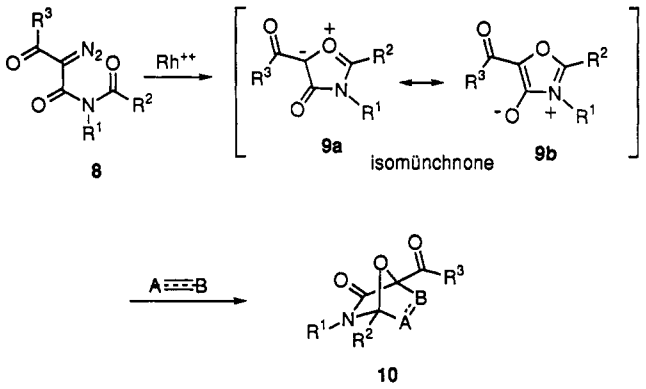
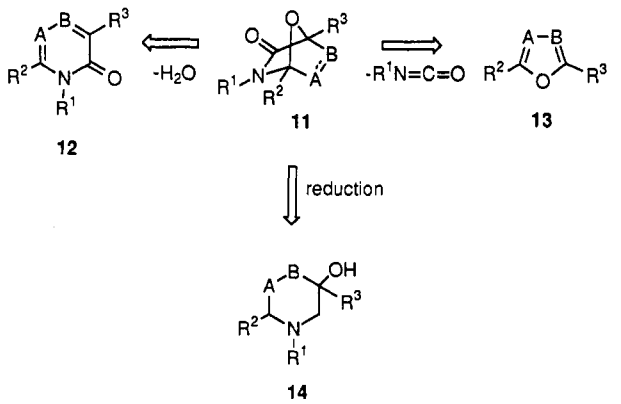
bonyl ylide dipole within their framework and are also willing participants in 1,3-dipolar cycloaddition. This class



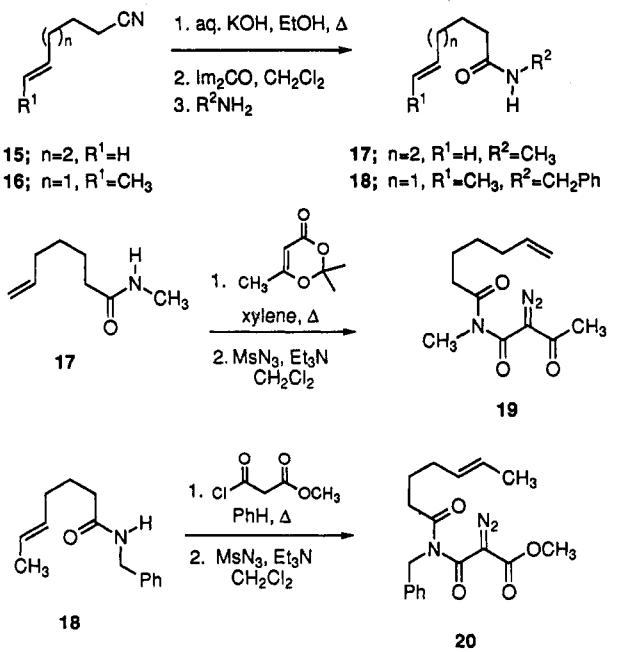
of mesoionics has been prepared by several different methods.[17-20] Our interest in the chemistry of isomünchnones stems from studies in our laboratory dealing with the rhodium(II)-catalyzed reactions of α-diazo carbonyl compounds in the presence of various heteroatoms.[21,22] In an earlier report we demonstrated that isomünchnones derived from the Rh(II)-catalyzed cyclization of diazo pyrrolidinones underwent cycloaddition with both electron-rich and electron-deficient dipolarophiles.[23]

Unlike the situation with sydnones and münchnones, the isomünchnone class of mesoionics offers the possibility of constructing several uniquely different heterocyclic systems from a common cycloadduct. Even though the bimolecular cycloaddition reaction of isomünchnones has been reported in the literature,[24] the range of their structural variation has remained somewhat narrow. In most instances, at least one of the substituents present on the isomünchnone backbone has been an aryl moiety,[24] presumably selected to facilitate dipole formation. In order to broaden the utility of these mesoionic compounds for synthesis, we thought it worthwhile to investigate the intramolecular cycloadditon of isomünchnones containing both alkenyl and alkynyl π-bonds.[25] As will be described below, the ability to synthesize a variety of polyheterocycles, functionalized lactams, and annulated furans from isomünchnones makes this class of mesoionics a rich source of functionality for the preparation of a wide range of biologically interesting molecules. The present paper documents the results of our studies in this area.



Results and Discussion

Intramolecular Cycloaddition of Acyclic Diazoimides. Construction of the prerequisite diazoimides necessary for dipole generation was accomplished by initial conversion of nitriles **15**[26] and **16**[27] to the corresponding carboxylic acids by basic hydrolysis in refluxing aqueous ethanol. Reaction with 1,1′-carbonyldiimidazole generated a transient acyl imidizolide which, when treated with the appropriate amine (R^2NH_2), gave the primary amides **17** and **18**. We have utilized several different synthetic protocols for introduction of the imide functionality. A typical approach involved heating the amide with 2,2,6-trimethyl-4*H*-1,3-dioxen-4-one[28] in xylene at 140 °C to give the N-acetoacylated amide. Another procedure involved malonylacylation of amide **18** with methyl malonyl chloride in refluxing benzene which produced the desired imide in quantitative yield. Exposure of these imides to standard diazo transfer conditions[29,30] (MsN_3, Et_3N) gave diazoimides **19** and **20** in good overall yield.



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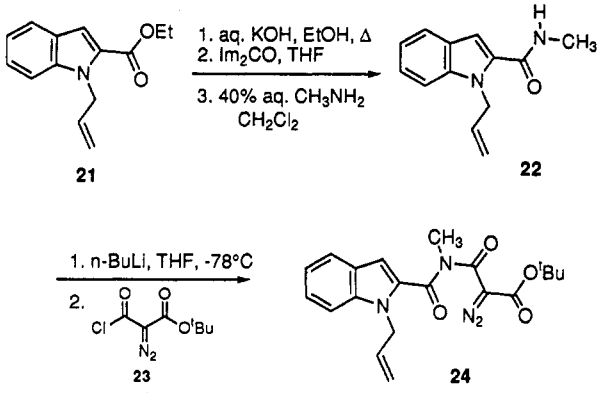
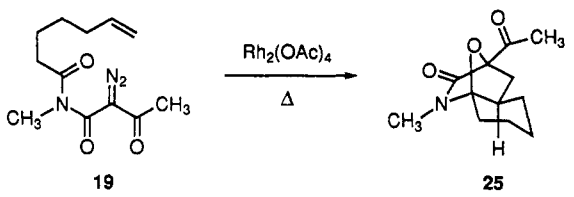
Occasionally, difficulties were encountered in the preparation of the diazoimides because the yield of diazo transfer was low or undesirable side reactions competed with the diazo transfer step. To avoid these problems, we developed an alternate and facile procedure which enables a one-pot preparation of the diazoimide under mild conditions. This new route involves formation of the diazoimide by reaction of an amide lithiate with ethyl or *tert*-butyl 2-diazomalonyl chloride. We have recently found that alkyl 2-diazomalonyl chlorides are efficient diazo acylating reagent for alcohols, amines, thiols, or amides.[31-34] This protocol was used for the preparation of diazoimide **24**. *N*-Allyl-1*H*-indole-2-carboxylic acid methylamide (**22**) was prepared by N-allylation of ethyl indole-2-carboxylate using allyl bromide in the presence of potassium *tert*-butoxide followed by conversion to the *N*-methylamide. Treatment of **22** with *n*-BuLi at −78 °C followed by the addition of *tert*-butyl 2-diazomalonyl chloride (**23**) gave diazoimide **24** in 73% overall yield. As



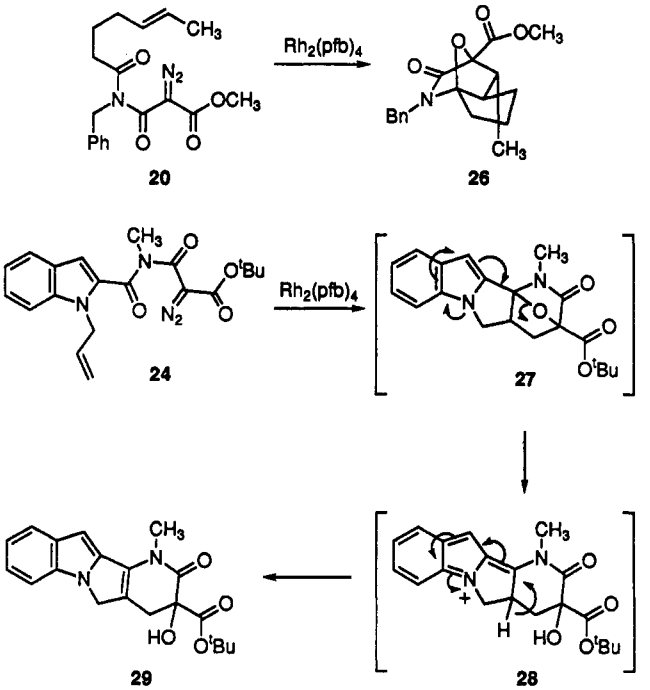
far as we can tell, this represents the first example where a diazoacylating agent has been used to prepare a diazoimide directly from an amide.

The Rh(II)-catalyzed decomposition of diazoimides results first in the formation of a rhodium carbenoid which then cyclizes onto the neighboring amide carbonyl oxygen to generate the intermediate isomünchnone.[23,25,35] Subsequent 1,3-dipolar cycloaddition across the pendant olefin affords the cycloadduct. A typical example of this sequence involves treating acyclic diazoimide **19** with a catalytic amount of rhodium(II) acetate in benzene (80 °C) which resulted in the formation of cycloadduct **25** as a single diastereomer in 71% isolated yield. The stereochemical assignment was based on comparison to an analogous cycloadduct whose structure had been deduced by X-ray crystallography.[25] Formation of cycloadduct **25** is the consequence of *endo* cycloaddition with regard to the dipole and this is in full accord with the lowest energy transition state (*vide infra*).



19 25

The tandem cyclization–cycloaddition sequence occurred under much milder conditions when rhodium(II) perfluorobutyrate was used as the catalyst. This is probably related to the fact that metal carbene reactions catalyzed by dirhodium(II) carboxylates are electrophilic in character, resembling those of a metal-stabilized carbocation.[36,37] Increased electron withdrawal by the ligand from the metal increases the electrophilicity of the carbene center and causes the loss of nitrogen to take place at a faster rate. Thus, treatment of diazoimide **20** in methylene chloride at room temperature resulted in a smooth tandem cyclization–cycloaddition producing cycloadduct **26** as a single diastereomer in 78% yield. The same reaction using



Rh(II) acetate required heating in benzene (80 °C) for much longer periods of time. Interestingly, when a sample of diazoimide **24** was allowed to react with a catalytic amount of rhodium(II) perfluorobutyrate in benzene at room temperature, compound **29** was obtained as the sole product in 90% yield. In this case, the initially formed cycloadduct **27** readily underwent a ring opening reaction to give **29**. Cleavage of the oxygen bridge most likely proceeds *via* iminium ion **28** which subsequently undergoes proton elimination to generate enamide **29**.

The bimolecular 1,3-dipolar cycloaddition of isomünchnones with alkynes is typically followed by extrusion of an alkyl or aryl isocyanate (RN=C=O) moiety to give substituted furans.[25,35] We were able to demonstrate that this pathway also occurred intramolecularly and this approach represents an efficient way to synthesize the annulated furan **32**. The intermediate cycloadduct **31**, generated from the transient isomünchnone derived from

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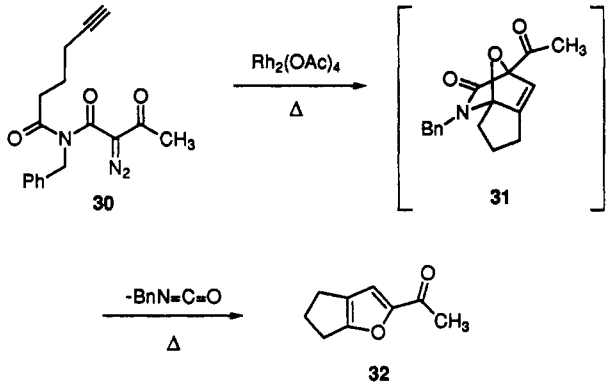
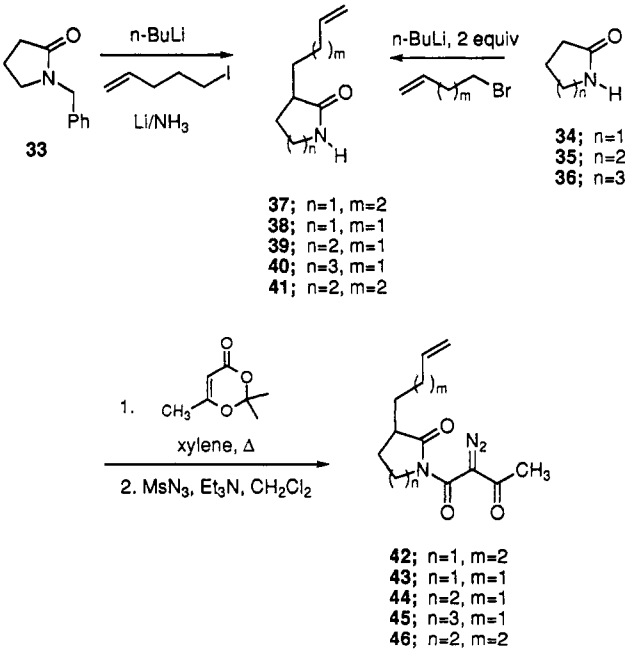
diazoimide **30**, could not be isolated. Instead, a rapid retro Diels–Alder reaction occurred resulting in the loss of benzyl isocyanate and giving rise to the isolated furan **32** in 84% yield.

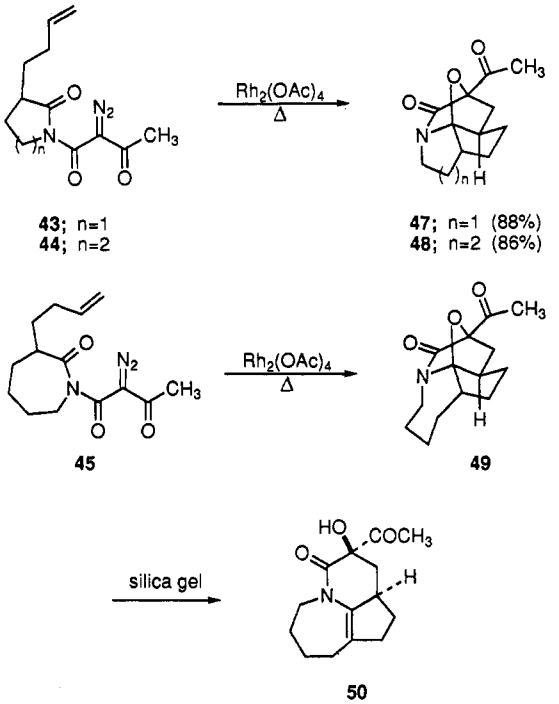


Intramolecular Cycloaddition of Cyclic Diazoimides. The complexity of the resultant cycloadducts could be significantly increased by generating isomünchnones where the peripheral substituents are part of a cyclic ring system. With this in mind, we decided to examine the Rh(II)-catalyzed behavior of a series of cyclic diazoimides containing tethered π-bonds. The initial strategy used to synthesize diazoimides **42–46** began by the alkenylation of *N*-benzylpyrrolidinone (**33**) with 5-iodopentene which produced the expected substituted lactam. Debenzylation with lithium in liquid ammonia afforded the C-alkenylated NH-lactam **37**. Subsequently, this sequence was shortened by adding 2 equiv of *n*-BuLi at low temperature (−78 °C) to the starting NH-lactam **34** followed by addition of the appropriate alkenyl halide.



Alkenylation of the amide dianion proceeded smoothly and in good yield with no significant quantities of any N-alkenylated product being formed. There was also no need for additional cosolvents (*i.e.* HMPA, DMPU) which are normally necessary in order to facilitate C-alkylation.[38-40] The substituted NH-lactams **37–41** were easily converted to the N-acetoacetylated products by reaction with 2,2,6-trimethyl-4*H*-1,3-dioxen-4-one in refluxing xylene. These were then transformed to diazoimides **42–46** in good yield using standard diazo transfer techniques (MsN_3, Et_3N).

Treatment of diazoimides **43** and **44** with a catalytic quantity of rhodium(II) acetate in benzene (80 °C) gave the polyheterocyclic systems **47** and **48** in excellent yield and with complete diastereospecificity. The stereochemistry of **47** was unambiguously determined through an X-ray crystallographic study.[41] Assignment of the stereochemistry of the closely related cycloadduct **48** is based on its spectroscopic properties and by analogy to **47**. When diazoimide **45** was allowed to react under the same experimental conditions, the crude reaction mixture showed only the presence of cycloadduct **49**. However,



purification by silica gel chromatography resulted in ring opening affording the tricyclic enamide **50** in addition to cycloadduct **49**. The structural assignment of **50** was unequivocally established by an X-ray crystal analysis.[41]

In recent years, molecular mechanics has developed into an important technique for the calculation of molecular properties.[42] We have used the Still–Steliou Model 2.94 program to model energy differences in the diastereomeric transition states for the two possible cycloadducts (*i.e. endo vs exo*). The stability of the diastereomeric cycloadducts was determined by calculation of their steric energies (*i.e.*, the direct sum of the force field increments). These steric energies represent the thermally averaged energies relative to the same molecule but with all bond lengths, bond angles, and torsional angles set to their strainless values and the atoms having van der Waals and electrostatic interactions corresponding to infinite separation.[43] We assume that the relative energy differences

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(41) The authors have deposited atomic coordinates for structures **47** and **50** with the Cambridge Crystallographic Data Centre. The coordinates can be obtained, on request, from the director, Cambridge Crystallographic Data Centre, 12 Union Road, Cambridge, CB2 1EZ, UK.
(42) Burkert, U.; Allinger, N. L. *Molecular Mechanics;* American Chemical Society: Washington, DC, 1982.
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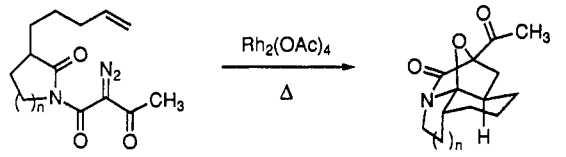
of the two lowest energy conformations of the regioisomeric cycloadducts will parallel the energy differences in the transition state. The *endo–exo* cycloadducts were subjected to energy minimization within the Model KS 2.94 program.[44] Global minima were found by making use of multiconformer generation in Model (TTY, Conf, Statistical, Coordinate) followed by Batch minimization using Bakmdl. The particular parameters used are those of the NOH (no hydrogen) field developed by Still and implemented by Steliou in the program Model. The resulting lowest energy conformations were then submitted to MMX for the calculations of strain energies.[45] The calculations reveal a 5.4-kcal difference between the *endo* and *exo* diastereomers of cycloadduct **47**, a 12.7-kcal difference with **48**, and a 9.4-kcal difference with **49**. The large differences in strain energy between the two diastereomers (and presumably the diasteromeric transition states) provides a reasonable explanation for why these internal isomünchnone reactions proceed exclusively *via* the *endo* orientation.

Diazoimides where the length of the alkenyl tether was increased by one methylene unit were also observed to undergo cycloaddition across the isomünchnone dipole. Thus, treatment of diazoimides **42** and **46** with a catalytic amount of rhodium(II) acetate in benzene (80 °C) gave cycloadducts **51** and **52** in high yield as single diastereomers. Their spectroscopic properties as well as molecular

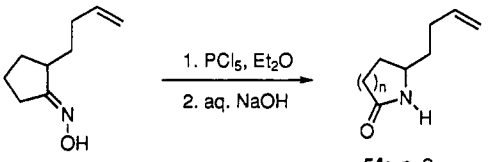


42; n=1
46; n=2

51; n=1 (71%)
52; n=2 (86%)

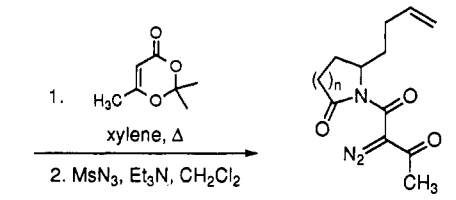
mechanics calculations support the stereochemical assignment of cycloadducts **51** and **52** as being the result of an *endo* cycloaddition. In particular, the corresponding *exo* isomer of cycloadduct **52** was calculated to be 8.2 kcal/mol higher in energy than its *endo* counterpart. The consequence of introducing a fourth methylene unit onto the alkenyl tether was that no cycloaddition occurred across the isomünchnone dipole. We assume that the length of the tether only influences the entropy of cyclization without affecting the rate of isomünchnone formation. Evidently the additional entropy introduced by the longer tether was sufficient to slow down intramolecular dipolar cycloaddition, thereby allowing other reactions to occur.

Another substitution variant that was also investigated corresponded to the placement of the alkenyl tether α to the amide nitrogen. The synthetic sequence used to prepare the diazo piperidine system **56** involved a Beckmann rearrangement[46] of oxime **53** which, in turn, was derived by oximation of 2-(3-butenyl)cyclopentan-1-one[47] with hydroxylamine hydrochloride in pyridine. The Beckmann rearrangement was induced by treating the oxime with PCl_5 in Et_2O followed by basic workup. The substituted alkenyl piperidone **54** was then converted in the normal manner to the corresponding diazoimide **56**.



53

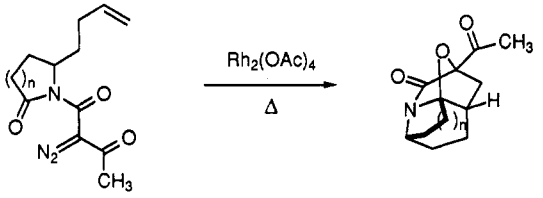
54; n=2
55; n=1



56; n=2
57; n=1

In the case of the five-membered pyrrolidine system, lactam **55** was also converted to diazoimide **57** *via* reaction with 2,2,6-trimethyl-4*H*-1,3-dioxen-4-one and subsequent diazo transfer.

Treatment of diazo imides **56** and **57** with a catalytic quantity of rhodium(II) acetate in benzene (80 °C) afforded the *exo* cycloadducts **58** and **59** in 69 and 76% yield, respectively. In this case, the length of the alkenyl tether



56; n=2
57; n=1

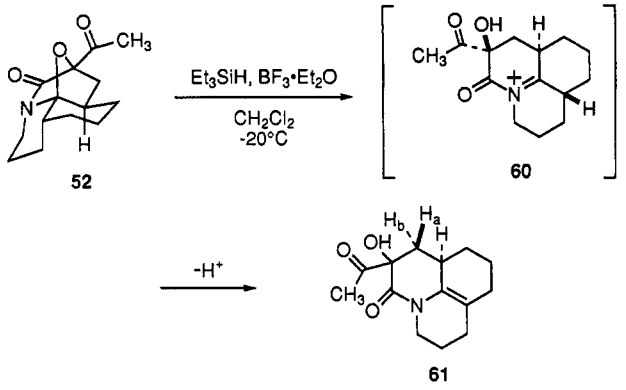
58; n=2 (76%)
59; n=1 (69%)

and its position on the lactam ring precludes formation of the *endo* cycloadduct. No cycloadducts could be isolated when the homologous derivatives of **56** or **57**, in which the alkenyl tether was either increased or decreased by one methylene unit, were subjected to rhodium(II)-catalyzed decomposition.[48] Improper alignment of the dipole–dipolarophile centers is presumably the key factor responsible for the lack of internal cycloaddition with the isomünchnone possessing the allyl side chain.

Reductive Cleavage of N,O-Ketal. Given the success in forming complex polyheterocyclic systems from the intramolecular isomünchnone cycloaddition reaction, it seemed to us that selective modification of the cycloadduct skeleton would allow application of the method toward alkaloid synthesis. In particular, reductive cleavage of the oxy bridge would provide ring systems containing both piperidine and quinoline skeletons so frequently found in the alkaloid kingdom.[49] In earlier reports, both Maier[25] and Meyers[50] have demonstrated that it is possible to selectively reduce N,O-ketals. Maier[25] utilized hydride donors such as Et_3SiH in the presence of Lewis acids. The Meyers[50] group showed that AlH_3 is a viable reducing reagent for the reductive ring opening of bicyclic lactams. Our attempts to selectively reduce some of the isomünch-

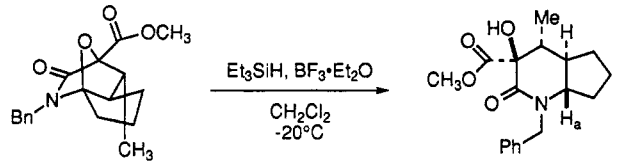
(44) We thank Professor Kosta Steliou of Boston University for providing a copy of the extensively rewritten Still Model program and for providing a VMS version of MMX.
(45) Gajewski, J. J.; Gilbert, K. E.; McKelvey, J. *Advances in Molecular Modeling;* Liotta, D., Ed.; JAI Press: Greenwich, CT, 1990; Vol. 2.
(46) Lalonde, R. T.; Muhammad, N.; Wong, C. F.; Sturiale, E. R. *J. Org. Chem.* **1980**, *45*, 3664.
(47) Molander, G.; McKie, J. A. *J. Org. Chem.* **1992**, *57*, 3132.
(48) For the preparation of the diazoimides used in these studies, see the Experimental Section.
(49) Stoll, A.; Hoffman, A. *The Alkaloids;* Manske, R. H. F., Ed.; Academic Press: San Diego, 1965, Vol. VIII, p 725.
(50) Burgess, L. E.; Meyers, A. I. *J. Org. Chem.* **1992**, *57*, 1656.

none derived cycloadducts with both of these reducing agents proved problematic. For example, treatment of cycloadduct **52** with Et_3SiH and BF_3–Et_2O gave enamide **61** as the exclusive product. The lone pair of electrons on



52 60 61

the amide nitrogen undoubtedly assists in opening the oxy bridge generating the *N*-acyliminium ion **60**. Unfortunately, proton loss from this transient species affords enamide **61** prior to reduction by Et_3SiH. Attempts to use a more powerful hydride donor such as Et_2SiH_2 also failed and, once again, only enamide **61** was isolated. On the other hand, when cycloadduct **26** was treated under similar reaction conditions, the reduced *trans* bicyclic perhydro-1-piperidine skeleton **62** was isolated in 93% yield. The relative stereochemistry of **62** was assigned on



26 62

the basis of the large *trans* diaxial coupling constant (J = 9.0 Hz) as well as the smaller coupling constant for the axial–equatorial coupling of proton H_a (J = 7.5 Hz). In this case, reduction of the transient *N*-acyliminium ion is much faster than proton loss and this is probably related to the ring strain imposed by the five-membered ring.

In conclusion, isomünchnones are easily accessible from α-diazoimides and represent versatile mesoionic compounds which are useful in organic synthesis. The structurally diverse group of heterocyclic compounds that have been prepared by the intramolecular dipolar cycloaddition of these mesoionics clearly demonstrates the high potential they have in organic synthesis. We are continuing to explore the scope, generality, and synthetic applications of the intramolecular isomünchnone cycloaddition reaction and will report additional findings at a later date.

Experimental Section

Melting points are uncorrected. Mass spectra were determined at an ionizing voltage of 70 eV. Unless otherwise noted, all reactions were performed in oven-dried glassware under an atmosphere of extra dry nitrogen. Solutions were evaporated under reduced pressure with a rotary evaporator and the residue was chromatographed on a silica gel column using an ethyl acetate–hexane mixture as the eluent unless specified otherwise.

General Procedure for the Acetoacetylation of Lactams. A variation of the procedure described by Kato and co-workers was used to prepare the desired ketolactams.[28] A solution containing 5 mmol of the appropriate lactam and 6 mmol of 2,2,6-trimethyl-1,3-dioxen-4-one in 5 mL of xylene was heated at reflux for 2 h. The solvent was removed under reduced pressure and the residue was purified by flash chromatography on a silica gel column.

General Procedure for the Synthesis of Diazoimides. A variation of the procedure described by Taber and co-workers[29] was used to prepare the diazoimide system. To a solution containing 2 mmol of the appropriate ketolactam and 2.2 mmol of mesyl azide in 5 mL of acetonitrile was added 4.0 mmol of NEt_3 under N_2 at rt. After the solution was stirred for 3 h, the solvent was removed under reduced pressure and the residue was subjected to flash chromatography on a silica gel column.

Preparation and Rhodium(II)-Catalyzed Cycloaddition of *N*-(Hept-6-enoyl)-*N*-methyl-2-diazo-3-oxobutyramide (19). A solution containing 3.46 g (31.7 mmol) of hept-6-enenitrile[26] (**15**) in 150 mL of 95% ethanol was treated with 17.8 g (317 mmol) of KOH in 60 mL of water and the mixture was heated at reflux for 12 h. The solution was cooled to rt and poured into 300 mL of 6 N HCl at 0 °C. The solution was extracted with ether, the combined ether extracts were dried over anhydrous $MgSO_4$ and filtered, and the solvent was removed under reduced pressure. The crude acid was taken up in 75 mL of dry THF and treated with 6.16 g (38.0 mmol) of 1,1′-carbonyl diimidazole under N_2 at rt for 2 h. To this solution was added 75 mL of 40% aqueous methylamine solution and the mixture was stirred at rt for 4 h. The solution was concentrated under reduced pressure, the residue was extracted with CH_2Cl_2, dried over anhydrous $MgSO_4$, and filtered, and the solvent was removed under reduced pressure. The resulting residue was subjected to flash silica gel chromatography to give 3.78 g (85%) of hept-6-enoic acid methylamide (**17**) as a clear oil: IR (neat) 1645, 1560, 1410, 1161 cm^{-1}; NMR ($CDCl_3$, 300 MHz) δ 1.33 (quin, 2H, J = 7.5 Hz), 1.59 (quin, 2H, J = 7.5 Hz), 1.97 (dt, 2H, J = 7.5 and 7.1 Hz), 2.11 (t, 2H, J = 7.5 Hz), 2.69 and 2.70 (s, 3H) (rotamers), 4.83–4.94 (m, 2H), 5.69 (ddt, 1H, J = 16.9, 10.2, and 7.1 Hz), 6.41 (s, 1H); ^{13}C-NMR ($CDCl_3$, 75 MHz) δ 25.1, 26.0, 28.4, 33.3, 36.2, 114.4, 138.2, 173.8.

A solution of 2.0 g (14.2 mmol) of the above amide and 2.04 mL (15.6 mmol) of 2,2,6-trimethyl-1,3-dioxin-4-one[28] in 15 mL of xylene was heated at reflux for 3 h and then cooled to rt and concentrated under reduced pressure. The orange residue was subjected to flash silica gel chromatography to give 1.8 g (56%) of *N*-(hept-6-enoyl)-*N*-methyl-3-oxobutyramide as a yellow oil: IR (neat) 1652, 1545, 1353, 1246 cm^{-1}; NMR ($CDCl_3$, 300 MHz) δ 1.35 (quin, 2H, J = 7.4 Hz), 1.56 (quin, 2H, J = 7.4 Hz), 1.98 (dt, 2H, J = 7.4 and 7.0 Hz), 2.17 (s, 3H), 2.47 (t, 2H, J = 7.4 Hz), 3.15 (s, 3H), 3.87 (s, 2H), 4.84–4.96 (m, 2H), 5.70 (ddt, 1H, J = 17.0, 10.2, and 7.0 Hz); ^{13}C-NMR ($CDCl_3$, 75 MHz) δ 3.6, 24.8, 28.0, 30.9, 33.2, 36.6, 54.3, 114.6, 138.1, 169.1, 175.5, 201.3.

A solution of 1.74 g (7.73 mmol) of the above compound in 50 mL of acetonitrile at 0 °C was treated with 1.12 g (9.28 mmol) of mesyl azide and then 2.58 mL (18.6 mmol) of NEt_3. The solution was stirred at rt for 4 h and the solvent was removed under reduced pressure. The residue was taken up in 100 mL of CH_2Cl_2, washed with NaOH, and brine, dried over anhydrous $MgSO_4$, and filtered, and the solvent was removed under reduced pressure. The residue was subjected to flash silica gel chromatography to give 1.29 g (66%) of *N*-(hept-6-enoyl)-*N*-methyl-2-diazo-3-oxobutyramide (**19**) as a bright yellow oil: IR (neat) 2136, 1659, 1360, 1254 cm^{-1}; NMR ($CDCl_3$, 300 MHz) δ 1.38 (quin, 2H, J = 7.3 Hz), 1.62 (quin, 2H, J = 7.3 Hz), 2.02 (dt, 2H, J = 7.3 and 6.6 Hz), 2.40 (s, 3H), 2.48 (t, 2H, J = 7.3 Hz), 3.15 (s, 3H), 4.87–4.99 (m, 2H) 5.73 (ddt, 1H, J = 17.0, 10.2, and 6.6 Hz); ^{13}C-NMR ($CDCl_3$, 75 MHz) δ 23.9, 28.2, 28.3, 33.0, 33.3, 35.8, 81.4, 114.7, 138.2, 165.0, 174.7, 189.2.

A solution of 0.21 g (0.86 mmol) of **19** in 10 mL of benzene was treated with a catalytic amount of rhodium(II) acetate and the mixture was heated at reflux under N_2 for 1.5 h. The solution was cooled to rt and the solvent was removed under reduced pressure. The residue was subjected to flash silica gel chromatography to give 135 mg (71%) of 8-acetyl-10-methyl-11-oxo-10-aza-tricyclo[6.2.1.0^{1,6}]undecan-9-one (**25**) as a clear oil: IR (neat) 1716, 1417, 1240, 1054 cm^{-1}; NMR ($CDCl_3$, 300 MHz) δ 1.02–1.19 (m, 2H), 1.42–1.90 (m, 7H), 2.00–2.13 (m, 2H), 2.25 (s, 3H), and 2.61 (s, 3H); ^{13}C-NMR ($CDCl_3$, 75 MHz) δ 21.0, 24.2, 24.8, 27.0, 27.1, 32.1, 36.7, 40.2, 90.5, 95.6, 171.2, and 200.6; HRMS calcd for $C_{12}H_{17}NO_3$ 223.1204, found 223.1208.

Preparation and Rhodium(II)-Catalyzed Cycloaddition of *N*-Benzyl-2-diazo-*N*-hept-5-enoylmalonamic Acid Methyl

Ester (20). A solution containing 1.20 g (5.52 mmol) of hept-5-enoic acid benzylamide[25] (18) in 25 mL of benzene under Ar was treated with 1.13 g (8.28 mmol) of methyl malonyl chloride and the mixture was heated at reflux for 1 h. The mixture was taken up in 100 mL of ether and washed with 10% aqueous NaOH and brine. The organic extracts were dried over $MgSO_4$, filtered, and concentrated under reduced pressure. The residue was subjected to flash silica gel chromatography to give 1.25 g (71%) of *N*-benzyl-*N*-hept-5-enoylmalonamic acid methyl ester as an oil: IR (neat) 2954, 1748, 1692, 1341 cm^{-1}; ^1H-NMR ($CDCl_3$, 300 MHz) δ 1.65–1.50 (m, 4H), 1.90 (q, 2H, J = 6.7 Hz), 2.46 (t, 2H, J = 7.3 Hz), 3.70 (s, 3H), 3.89 (s, 2H), 4.97 (s, 2H), 5.38–5.15 (m, 2H), and 7.40–7.15 (m, 5H); ^{13}C-NMR ($CDCl_3$, 70 MHz) δ 17.7, 23.9, 31.4, 35.7, 46.2, 46.8, 52.2, 126.0, 127.3, 128.8, 129.9, 136.4, 167.8, 168.6, 176.1.

A solution of 1.0 g (3.15 mmol) of the above *N*-benzyl imide in 25 mL of CH_2Cl_2 under Ar at 0 °C was treated with 0.76 g (6.30 mmol) of mesyl azide and 0.96 g (9.45 mmol) of Et_3N. The residue was warmed to rt and stirred for 8 h. The solution was taken up in 100 mL of ether and washed with 10% aqueous NaOH and brine. The organic extracts were dried over $MgSO_4$, filtered, and concentrated under reduced pressure. The residue was subjected to flash silica gel chromatography to give 0.92 g (85%) of *N*-benzyl-2-diazo-*N*-hept-5-enoylmalonamic acid methyl ester (20) as a yellow oil: IR (neat) 2136, 1719, 1640, 1127 cm^{-1}; ^1H-NMR ($CDCl_3$, 300 MHz) δ 1.70–1.50 (m, 4H), 1.92 (q, 2H, J = 6.6 Hz), 2.44 (t, 2H, J = 7.4 Hz), 3.78 (s, 3H), 4.88 (s, 2H), 5.42–5.30 (m, 2H), 7.35–7.20 (m, 5H); ^{13}C-NMR ($CDCl_3$, 75 MHz) δ 17.8, 24.3, 31.5, 35.2, 49.0, 52.3, 72.6, 125.8, 126.9, 127.4, 128.6, 130.1, 137.0, 160.8, 166.0, 175.7.

To a solution of 0.92 g (2.68 mmol) of the above diazo imide 20 in 20 mL of CH_2Cl_2 under Ar at rt was added a catalytic amount of $Rh_2(pfb)_4$. The mixture was stirred at rt for 4 h. The solution was concentrated under reduced pressure and the residue was subjected to flash silica gel chromatography to give 0.66 g (78%) of 9-benzyl-6-methyl-8-oxo-10-oxa-9-azatricyclo[5.2.1.$0^{1,5}$]-decane-7-carboxylic acid methyl ester (26) as a white solid: mp 92–93 °C; IR (neat) 2960, 1748, 1692, 1125 cm^{-1}; ^1H-NMR ($CDCl_3$, 300 MHz) δ 1.17 (d, 3H, J = 6.9 Hz), 1.40 (m, 1H), 1.58 (td, 1H, J = 8.6 and 3.5 Hz), 1.70 (m, 1H), 1.92 (m, 4H), 2.35 (m, 1H), 3.75 (s, 3H), 4.45 (AB, 2H, J = 15.6 Hz, $\Delta\nu$ = 62.7 Hz), and 7.33–7.20 (m, 5H); ^{13}C-NMR ($CDCl_3$, 75 MHz) δ 15.1, 24.5, 25.5, 29.6, 43.2, 44.7, 52.6, 55.5, 91.0, 105.9, 127.6, 128.6, 136.5, 166.1, 169.2; HRMS calcd for $C_{18}H_{21}NO_4$ C, 68.54; H, 6.72; N, 4.44, found C, 68.41; H, 6.70; N, 4.28.

Preparation of *tert*-Butyl Diazomalonyl Chloride (23). A solution containing 25.0 g (84.23 mmol) of triphosgene in 100 mL of benzene was cooled to 0 °C in an ice bath and was then treated with 0.7 mL (10 mol%) of pyridine. To the resulting mixture was added 24.0 g (169.9 mmol) of *tert*-butyl diazoacetate at a rate at which the reaction temperature did not rise above 10 °C. The mixture was stirred at 0 °C for 2 h and was then allowed to warm to rt and was stirred for an additional 12 h. The solution was filtered through a pad of Celite and was concentrated under reduced pressure. The resulting red oil was distilled at 82–84 °C (1 mm) to give 18 g (52%) of *tert*-butyl diazomalonyl chloride (23) as a yellow oil which solidified upon standing at 0 °C; IR (neat) 1775, 1695, 1303, 1143 cm^{-1}; NMR ($CDCl_3$, 300 MHz) δ 1.47 (s, 9H); ^{13}C-NMR ($CDCl_3$, 75 MHz) δ 27.5, 28.0, 63.5, 84.9, 157.2, 161.0.

Preparation and Rhodium(II)-Catalyzed Cycloaddition of 3-[[(1-Allyl-1*H*-indol-2-ylcarbonyl]methylamino]-2-diazo-3-oxopropionic Acid *tert*-Butyl Ester (24). A stirred slurry containing 6.53 g (58.0 mmol) of KOtBu in 100 mL of THF was treated with 10.0 g (53.0 mmol) of ethyl indole-2-carboxylate. To this solution was added 5.50 mL (63.0 mmol) of allyl bromide and the mixture was heated at reflux for 18 h. The reaction was quenched with a saturated NH_4Cl solution, the organic layer was separated, and the aqueous layer was extracted with ether. The combined ether extracts were washed with a saturated NaCl solution, dried over anhydrous $MgSO_4$, and concentrated under reduced pressure. The residue was subjected to flash chromatography on silica gel to give 1-allyl-1*H*-indole-2-carboxylic acid ethyl ester (21) as a yellow oil (77%): IR (neat) 1713, 1459, 1196, 1140 cm^{-1}; NMR ($CDCl_3$, 300 MHz) δ 1.46 (t, 3H, J = 7.2 Hz), 4.43 (q, 2H, J = 7.2 Hz), 4.94–5.26 (m, 4H), 6.02–6.12 (m, 1H), 7.20–7.77 (m, 5H); ^{13}C-NMR ($CDCl_3$, 75 MHz) δ 14.3, 46.6, 60.4, 110.6, 115.9, 120.7, 122.6, 125.0, 126.0, 127.4, 133.9, 139.1, 161.8.

A solution of 9.34 g (40.8 mmol) of the above ester in 150 mL of absolute ethanol was treated with 80 mL of 1 N KOH. The solution was allowed to stir at rt for 24 h and was then concentrated under reduced pressure. The residue was taken up in 100 mL of H_2O, washed with 20 mL of ether, acidified to pH 2 with 10% HCl, and extracted with CH_2Cl_2. The combined organic extracts were washed with a saturated NaCl solution, dried over anhydrous $MgSO_4$, and concentrated under reduced pressure to give 1-allyl-1*H*-indole-2-carboxylic acid (91%) as white crystals; mp 183–184 °C; IR (KBr) 1678, 1513, 1268 cm^{-1}; NMR ($CDCl_3$, 300 MHz) δ 4.87–5.22 (m, 4H), 5.95–6.07 (m, 1H), 7.14–7.72 (m, 5H); ^{13}C-NMR ($CDCl_3$, 75 MHz) δ 46.7, 110.6, 112.8, 116.0, 120.8, 122.8, 125.7, 125.8, 125.9, 133.6, 139.6, 166.0.

A solution of 2.01 g (10.0 mmol) of the above carboxylic acid in 50 mL of THF was treated with 1.78 g (11.0 mmol) of 1,1′-carbonyldiimidazole. The solution was allowed to stir at rt for 12 h and then poured into a solution of 100 mL of 40% aqueous methylamine solution which contained 25 g of crushed ice. The solution was allowed to warm to rt, stirred for 5 h, and was concentrated under reduced pressure. The residue was extracted with CH_2Cl_2, the combined organic extracts were dried over anhydrous $MgSO_4$ and filtered, and the solvent was removed under reduced pressure to give 1-allyl-1*H*-indole-2-carboxylic acid methylamide (22) (82%) as a white solid: mp 112–113 °C; IR (KBr) 1639, 1545, 1442, 1402 cm^{-1}; NMR ($CDCl_3$, 300 MHz) δ 2.99 (d, 3H, J = 5.0 Hz), 4.90–5.25 (m, 4H), 5.95-6.10 (m, 1H), 6.27 (brs, 1H), 6.82 (s, 1H), 7.10–7.70 (m, 4H); ^{13}C-NMR ($CDCl_3$, 75 MHz) δ 26.4, 46.8, 104.5, 110.6, 116.0, 120.6, 121.8, 124.1, 126.2, 134.2, 135.1, 138.4, 163.3. Anal. Calcd for $C_{13}H_{14}N_2O$: C, 72.87; H, 6.59; N, 13.07. Found: C, 72.81; H, 6.60; N, 13.02.

A solution containing 750 mg (3.5 mmol) of the above amide 22 in 30 mL of THF was cooled to −78 °C. To this solution was added 2.45 mL (3.9 mmol) of a 1.60 M *n*-butyllithium solution in hexane. The resulting orange solution was stirred for 20 min at −78 °C and then 0.79 g (3.9 mmol) of *tert*-butyl diazomalonyl chloride (23) was added dropwise. The solution was allowed to stir at −78 °C for 1 h at which time the reaction was quenched with H_2O. The organic layer was separated and the aqueous layer was extracted with ether and CH_2Cl_2. The combined organic extracts were washed with a saturated NaCl solution, dried over anhydrous $MgSO_4$, and concentrated under reduced pressure. The residue was subjected to flash silica gel chromatography to give of 3-[[(1-allyl-1*H*-indol-2-ylcarbonyl]methylamino]-2-diazo-3-oxopropionic acid *tert*-butyl ester (24) (73%) as a bright yellow oil: IR (neat) 2150, 1780, 1702, 1311 cm^{-1}; NMR ($CDCl_3$, 300 MHz) δ 1.26–1.47 (s, 9H), 3.41–3.43 (s, 3H), 4.92–5.20 (m, 4H), 5.91–6.16 (m, 1H), 6.80–7.70 (m, 5H); ^{13}C-NMR ($CDCl_3$, 75 MHz) δ 28.0, 33.7, 36.3, 46.7, 58.9, 83.4, 109.4, 110.7, 116.6, 120.7, 125.2, 126.1, 131.7, 133.5, 138.9, 159.7, 163.7, 166.3.

To a solution containing 0.05 g (0.13 mmol) of 24 in 5 mL benzene was added 2 mg of rhodium(II) perfluorobutyrate and the solution was allowed to stir at rt for 45 min. The solution was then concentrated under reduced pressure and the residue was subjected to flash silica gel chromatography to give 3-hydroxy-1-methyl-2-oxo-2,3,4,5-tetrahydro-1*H*-pyrido[2′,3′:3,4]pyrrolo-[1,2-*a*]indole-3-carboxylic acid *tert*-butyl ester (29) (90%) as a white solid: mp 185–186 °C; IR (neat) 3408 (br), 2976, 1729, 1655, 1495, 1099 cm^{-1}; NMR ($CDCl_3$, 300 MHz) δ 1.30 (s, 9H), 2.88 (d, 1H, J = 15.2 Hz), 3.45 (d, 1H, J = 15.2 Hz), 3.45 (s, 3H), 3.95 (d, 1H, J = 21.3 Hz), 3.99, (d, 1H, J = 21.3 Hz), 6.82 (s, 1H), 7.00–7.40 (m, 4H); ^{13}C-NMR ($CDCl_3$, 75 MHz) δ 27.7, 29.2, 30.2, 31.4, 75.8, 82.7, 105.9, 109.3, 110.8, 118.7, 121.2, 123.1, 125.8, 127.8, 133.0, 140.5, 167.8, 169.7; HRMS calcd for $C_{20}H_{22}N_2O_4$ (M^+ + Li) 361.1739, found 361.1733.

Preparation and Rhodium(II)-Catalyzed Cycloaddition of *N*-Benzyl-*N*-(hex-5-ynoyl)-2-diazo-3-oxobutyramide (30). To a solution of 3.0 g (26.8 mmol) of 5-hexynoic acid in 50 mL of ether under N_2 was added 4.77 (29.5 mmol) of 1,1′-carbonyl diimidazole and the mixture was stirred at rt for 2 h. This solution was added to 7.3 mL (67 mmol) of benzylamine in 50 mL of ether at 0 °C. After the addition was complete, the solution was allowed to stir 4 h. The solvent was removed under reduced pressure the residue was taken up in 100 mL of CH_2Cl_2, washed with 10% HCl, brine, dried over anhydrous $MgSO_4$, and filtered and the solvent was removed under reduced pressure. The resulting

yellow solid was recrystallized from diisopropyl ether and pentane to give 5.17 g (96%) of 5-hexynoic acid benzylamide as a white solid: mp 56–57 °C; IR ($CHCl_3$) 1682, 1530, 1475 cm^{-1}; NMR ($CDCl_3$, 300 MHz) δ 1.77 (quin, 2H, J = 7.1 Hz), 1.92 (t, 1H, J = 2.5 Hz), 2.16 (td, 2H, J = 7.1 and 2.5 Hz), 2.26 (t, 2H, J = 7.1 Hz), 4.31 (d, 2H, J = 5.7 Hz), 6.55 (brs, 1H), and 7.10–7.38 (m, 5H); ^{13}C-NMR ($CDCl_3$, 75 MHz) δ 17.7, 24.0, 34.7, 43.2, 69.0, 83.3, 127.1, 127.4, 128.4, 138.2, 172.1.

N-Acetoacetylation was carried out on the above amide in the normal manner to give *N*-benzyl-*N*-(hex-5-ynoyl)-3-oxobutyramide (46%) as a light yellow oil: IR (neat) 1695, 1381, 1353, 1154 cm^{-1}; NMR ($CDCl_3$, 300 MHz) δ 1.67 (quin, 2H, J = 7.0 Hz), 1.83 (t, 1H, J = 2.6 Hz), 2.07 (td, 2H, J = 7.0 and 2.6 Hz), 2.20 (s, 3H), 2.54 (t, 2H, J = 7.0 Hz), 3.97 (s, 2H), 4.96 (s, 2H), 7.15–7.32 (m, 5H); ^{13}C-NMR ($CDCl_3$, 75 MHz) δ 17.1, 22.6, 29.7, 34.7, 46.4, 54.3, 69.1, 82.8, 125.8, 127.1, 128.6, 136.2, 169.0, 175.2, 201.2.

Diazo transfer of the above compound gave *N*-benzyl-*N*-(hex-5-ynoyl)-2-diazo-3-oxobutyramide (**30**) (76%) as a bright yellow oil: IR (neat) 2129, 1666, 1317, 1154 cm^{-1}; NMR ($CDCl_3$, 300 MHz) δ 1.74 (quin, 2H, J = 6.9 Hz), 1.87 (t, 1H, J = 2.6 Hz), 2.12 (td, 2H, J = 6.9 and 2.6 Hz), 2.33 (s, 3H), 2.56 (t, 2H, J = 6.9 Hz), 4.83 (s, 2H), 7.16–7.29 (m, 5H); ^{13}C-NMR ($CDCl_3$, 75 MHz) δ 17.3, 22.9, 28.0, 34.1, 48.8, 69.4, 81.8, 82.8, 126.7, 127.6, 128.7, 136.3, 164.8, 174.2, 188.4.

To a solution of 0.10 g (0.34 mmol) of **30** in 10 mL of benzene was added a catalytic amount of rhodium(II) acetate and the mixture was heated at reflux under N_2 for 2 h. The solution was cooled to rt and concentrated under reduced pressure. The residue was subjected to flash silica gel chromatography to give 90 mg (90%) of 1-(5,6-dihydro-4*H*-cyclopenta[*a*]furan-2-yl)-ethanone (**32**) as a clear oil: IR (neat) 1707, 1665, 1497, 1173 cm^{-1}; NMR ($CDCl_3$, 300 MHz) δ 2.31 (s, 3H), 2.33–2.44 (m, 2H), 2.48–2.53 (m, 2H), 2.66 (t, 2H, J = 7.2 Hz), 6.94 (s, 1H); ^{13}C-NMR ($CDCl_3$, 75 MHz) δ 22.8, 24.6, 25.3, 27.4, 115.8, 128.4, 156.7, 166.0, 185.9; HRMS calcd for $C_9H_{10}O_2$ 150.0678, found 150.0681.

Preparation and Rhodium(II)-Catalyzed Cycloaddition of 1-[2-Oxo-3-(pent-4-enyl)pyrrolidin-1-yl]-2-diazobutane-1,3-dione (42). To a solution of 5.24 mL (37.4 mmol) of diisopropylamine in 150 mL of THF at 0 °C was added 23.4 mL (37.4 mmol) of *n*-butyllithium in hexane. The solution was cooled to −78 °C, 6.0 g (34.0 mmol) of *N*-benzyl-2-pyrrolidinone was added in 10 mL of THF *via* syringe, and the mixture was stirred for 20 min. The resulting yellow solution was treated with 8.0 g (40.8 mmol) of 5-iodopentene in 10 mL of dry THF. The solution was allowed to warm to rt and stirred overnight. The solution was quenched with a saturated NH_4Cl solution and extracted with ether. The combined organic layer was dried over anhydrous $MgSO_4$, filtered, and concentrated under reduced pressure. The residue was subjected to flash silica gel chromatography to give 6.34 g (77%) of 1-benzyl-3-(pent-4-enyl)-2-pyrrolidinone as a light yellow oil: IR (neat) 1685, 1500, 1265 cm^{-1}; NMR ($CDCl_3$, 300 MHz) δ 1.30–1.50 (m, 3H), 1.57 (dq, 1H, J = 12.8 and 8.4 Hz), 1.80–1.94 (m, 1H), 2.00–2.18 (m, 3H), 2.38–2.46 (m, 1H), 3.10-3.17 (m, 2H), 4.41 (AB, 2H, J = 14.7 Hz), 4.90–5.01 (m, 2H), 5.78 (ddt, 1H, J = 17.0, 10.2, and 6.7 Hz), 7.17–7.30 (m, 5H); ^{13}C-NMR ($CDCl_3$, 75 MHz) δ 24.6, 26.3, 30.7, 33.5, 41.6, 44.6, 46.4, 114.5, 127.2, 127.8, 128.4, 136.5, 138.5, 176.4.

To a flame-dried 250-mL three-neck round-bottom flask equipped with two rubber septa and a dry ice condenser was added 100 mL of liquid ammonia at −78 °C. To the liquid ammonia were added 7.0 g (28.8 mmol) of 1-benzyl-3-(pent-4-enyl)-2-pyrrolidinone in 20 mL of THF, 1.69 mL (28.8 mmol) of absolute ethanol, and 0.81 g (115.2 mmol) of lithium wire. After the reaction was complete, the solution was quenched with 15.4 g (288 mmol) of solid NH_4Cl. The ammonia was allowed to evaporate overnight and the residue was taken up in ethyl acetate and washed with 10% $KHSO_4$. The aqueous layer was extracted with ethyl acetate, and the combined organic extracts were dried over anhydrous $MgSO_4$, filtered, and concentrated under reduced pressure. The residue was subjected to flash silica gel chromatography to give 4.0 g (91%) of 3-(pent-4-enyl)-2-pyrrolidinone (**37**) as a colorless oil: IR (neat) 1705, 1437, 1280 cm^{-1}; NMR ($CDCl_3$, 300 MHz) δ 1.17–1.40 (m, 3H), 1.57–1.76 (m, 2H), 1.96 (dt, 2H, J = 6.7 Hz), 2.09–2.28 (m, 2H), 3.17–3.25 (m, 2H), 4.81–4.91 (m, 2H), 5.69 (ddt, 1H, J = 16.9, 10.2 and 6.7 Hz), 7.54 (s, 1H); ^{13}C-NMR ($CDCl_3$, 75 MHz) δ 26.3, 27.1, 30.1, 33.4, 40.3, 40.8, 114.3, 138.1, 180.9.

N-Acetoacetylation was carried out on the above compound to give 1-[2-oxo-3-(pent-4-enyl)pyrrolidin-1-yl]butane-1,3-dione (47%): IR (neat) 1745, 1360, 1175 cm^{-1}; NMR ($CDCl_3$, 300 MHz) δ 1.30–1.45 (m, 3H), 1.56–1.64 (m, 1H), 1.70–1.83 (m, 1H), 1.94–2.07 (m, 2H), 2.13–2.18 (m, 1H), 2.18 (s, 3H), 2.42–2.60 (m, 1H), 3.51–3.60 (m, 1H), 3.83 (dt, 1H, J = 10.2, and 6.7 Hz), 3.90 (AB, 2H, J = 16.4 Hz), 4.86–4.96 (m, 2H), 5.73 (ddt, 1H, J = 16.9, 10.2, and 6.7 Hz); ^{13}C-NMR ($CDCl_3$, 75 MHz) δ 23.5, 25.9, 29.5, 29.9, 33.2, 42.9, 43.7, 52.1, 114.7, 137.8, 166.8, 177.3, 201.1.

Diazo transfer of the above compound gave 1-[2-oxo-3-(pent-4-enyl)pyrrolidin-1-yl]-2-diazobutane-1,3-dione (**42**) (80%): IR (neat) 2136, 1730, 1360, 1253 cm^{-1}; NMR ($CDCl_3$, 300 MHz) δ 1.31–1.43 (m, 3H), 1.62–1.80 (m, 2H), 1.93–2.05 (m, 2H), 2.15–2.22 (m, 1H), 2.37 (s, 3H), 2.48–2.60 (m, 1H), 3.60-3.80 (m, 2H), 4.85–4.95 (m, 2H), 5.70 (ddt, 1H, J = 16.9, 10.2 and 6.7 Hz); ^{13}C-NMR ($CDCl_3$, 75 MHz) δ 24.0, 25.9, 28.4, 29.6, 33.2, 43.5, 44.2, 79.8, 114.8, 137.7, 160.0, 175.8, 189.9.

To a solution of 0.19 g (0.72 mmol) of **42** in 15 mL of benzene was added 2 mg of rhodium(II) acetate and the mixture was heated at reflux for 3 h. The solution was cooled to rt and concentrated under reduced pressure. The residue was recrystallized from CH_2Cl_2–hexane to give 0.12 g (71%) of 5-acetyl-1,2,5,6,6a,7,8,9,9a,9b-decahydro-5,9b-epoxy-4-oxopyrrolo[3,2,1-*ij*]quinoline (**51**) as a white solid: mp 96–97 °C; IR ($CHCl_3$) 1735, 1705, 1455 cm^{-1}; NMR ($CDCl_3$, 300 MHz) δ 1.14 (dq, 1H, J = 12.9 and 2.5 Hz), 1.35–1.51 (m, 1H), 1.57–1.89 (m, 5H), 2.03–2.28 (m, 3H), 2.38 (s, 3H), 2.61–2.72 (m, 1H), 3.39–3.45 (m, 3H); ^{13}C-NMR ($CDCl_3$, 75 MHz) δ 20.6, 23.5, 27.2, 29.7, 31.1, 33.4, 33.5, 39.2, 41.5, 96.1, 100.1, 167.1, 200.8. Anal. Calcd for $C_{13}H_{17}NO_3$: C, 66.36; H, 7.28; N, 5.95. Found: C, 66.46; H, 7.31; N, 5.97.

Preparation and Rhodium(II)-Catalyzed Cycloaddition of 1-[2-Oxo-3-(but-3-enyl)pyrrolidinyl]-2-diazobutane-1,3-dione (43). A solution containing 1.0 g (11.1 mmol) of 2-pyrrolidinone in 50 mL of distilled THF was cooled to 0 °C under N_2. To this solution was added 15.4 mL (24.6 mmol) of a 1.60 M *n*-butyllithium solution in hexane. The resulting solution was stirred for 70 min at 0 °C and then a solution containing 1.90 g (14.1 mmol) of 1-bromo-3-butene in 5 mL of THF was added *via* syringe. The resulting solution was allowed to stir for 45 min at 0 °C and was then warmed to 25 °C and stirred for an additional 2 h. The reaction was quenched with a saturated NH_4Cl solution. The organic layer was separated and the aqueous layer was extracted with CH_2Cl_2. The combined organic extracts were washed with a saturated NaCl solution, dried over $MgSO_4$, and concentrated under reduced pressure. The resulting residue was subjected to flash chromatography on silica gel to give 311 mg (21%) of a clear oil whose structure was assigned as 3-(but-3-enyl)pyrrolidin-2-one (**38**) on the basis of its spectral properties: IR (neat) 1695, 1460, 1285, 1270, 915 cm^{-1}; NMR ($CDCl_3$, 300 MHz) δ 1.18–1.50 (m, 1H), 1.68–1.88 (m, 1H), 1.90–2.21 (m, 5H), 3.20–3.40 (m, 2H), 4.94 (d, 1H, J = 10.3 Hz), 5.02 (d, 1H, J = 17.3 Hz), 5.70–5.87 (m, 1H), 6.87 (brs, 1H).

N-Acetoacetylation of the above compound in the standard manner gave 1-[2-oxo-3-(but-3-enyl)pyrrolidinyl]butane-1,3-dione as a pale yellow oil (58%): IR (neat) 1745, 1380, 1260, 1175 cm^{-1}; NMR ($CDCl_3$, 90 MHz) δ 1.20–2.00 (m, 3H), 2.03–2.35 (m, 3H), 2.28 (s, 3H), 2.35–2.85 (m, 1H), 3.43–4.15 (m, 2H), 4.02 (s, 2H), 4.93–5.27 (m, 2H), 5.60–6.10 (m, 1H).

Diazo transfer of the above compound gave 1-[2-oxo-3-(but-3-enyl)pyrrolidinyl]-2-diazobutane-1,3-dione (**43**) as a bright yellow oil (88%): IR (neat) 2160, 1745, 1670, 1210, 760 cm^{-1}; NMR ($CDCl_3$, 300 MHz) δ 1.31–1.48 (m, 1H), 1.53–1.70 (m, 1H), 1.77–1.91 (m, 1H), 1.93–2.22 (m, 3H), 2.32 (s, 3H), 2.42–2.57 (m, 1H), 3.52–3.75 (m, 2H), 3.87 (d, 1H, J = 10.6 Hz), 4.92 (d, 1H, J = 19.0 Hz), 5.55–5.75 (m, 1H).

A mixture containing 98 mg (0.39 mmol) of **43** in 8 mL of benzene and 2 mg of rhodium(II) acetate dimer was heated at reflux for 3 h. The solvent was removed under reduced pressure and the residue was subjected to flash chromatography to give 76 mg (88%) of 5-acetyl-1,2,4,5,6,6a,7,8,8a,8b-decahydro-5,8b-epoxy-4-oxocyclopent[*hi*]indolizine (**47**) as a white crystalline solid: mp 79–80 °C; IR ($CHCl_3$) 1735, 1460, 1380, 1250, 1085 cm^{-1}; ^1H-NMR ($CDCl_3$, 300 MHz) δ 1.42–1.69 (m, 2H), 1.70–1.80 (m, 1H), 1.85–2.08 (m, 2H), 2.16–2.40 (m, 3H), 2.28 (s, 3H), 2.52–2.67 (m, 2H), 3.40–3.62 (m, 2H); ^{13}C-NMR ($CDCl_3$, 75 MHz) δ

26.4, 31.9, 32.2, 33.5, 34.2, 35.1, 41.3, 46.8, 99.8, 113.9, 166.1, 199.9. Anal. Calcd for $C_{12}H_{15}NO_3$: C, 65.14; H, 6.83; N, 6.33. Found: C, 65.09; H, 6.83; N, 6.38.

Preparation and Rhodium(II)-Catalyzed Cycloaddition of 1-[2-Oxo-3-(but-3-enyl)piperidinyl]-2-diazobutane-1,3-dione (44). A solution containing 3.04 g (30.7 mmol) of 2-piperidone in 150 mL of dry THF was cooled to 0 °C under N_2. To this solution was added 41 mL (65.6 mmol) of a 1.60 M *n*-butyllithium solution in hexane. The resulting solution was stirred at 0 °C for 1 h and then a solution containing 4.97 g (36.8 mmol) of 4-bromo-1-butene in 15 mL of dry THF was added *via* syringe. The resulting solution was stirred for 45 min at 0 °C and was then warmed to 25 °C and stirred for an additional 1 h. At the end of this time, the reaction was quenched with 10 mL of a saturated NH_4Cl solution. An additional 20 mL of water was added and the organic layer was separated. The aqueous layer was extracted with CH_2Cl_2 and the combined organic layer was dried over $MgSO_4$ and concentrated under reduced pressure. The residue was subjected to silica flash chromatography to give 3-(but-3-enyl)piperidin-2-one (**39**) (76%): mp 56–57 °C; IR ($CHCl_3$) 1655, 1500, 1455, 925 cm^{-1}; NMR ($CDCl_3$, 300 MHz) δ 1.38–1.56 (m, 2H), 1.57–1.71 (m, 1H), 1.73–2.40 (m, 6H), 3.12–3.40 (m, 2H), 4.90 (d, 1H, J = 10.2 Hz), 4.99 (d, 1H, J = 17.4 Hz), 5.65–5.90 (m, 1H), 6.70–7.10 (brs, 1H). Anal. Calcd for $C_9H_{15}NO$: C, 70.55; H, 9.87; N, 9.14. Found: C, 70.47; H, 9.89; N, 9.06.

N-Acetoacetylation of the above compound in the standard manner gave 1-[2-oxo-3-(but-3-enyl)piperidinyl]butane-1,3-dione as a pale yellow oil (65%): IR (neat) 1715, 1680, 1455, 1360, 740 cm^{-1}; NMR ($CDCl_3$, 300 MHz) δ 1.25–1.41 (m, 2H), 1.55–2.04 (m, 6H), 2.08 (s, 3H), 2.21–2.32 (m, 1H), 3.40–3.52 (m, 1H), 3.67–3.80 (m, 1H), 3.79 (s, 2H), 4.79 (d, 1H, J = 10.4 Hz), 4.86 (d, 1H, J = 17.5 Hz), 5.53–5.68 (m, 1H).

Diazo transfer of the above compound gave 1-[2-oxo-3-(but-3-enyl)piperidinyl]-2-diazobutane-1,3-dione (**44**) as a bright yellow oil (84%): IR (neat) 2150, 1665, 1400, 1245, 920 cm^{-1}; NMR ($CDCl_3$, 300 MHz) δ 1.45–1.62 (m, 2H), 1.78–2.20 (m, 6H), 2.40–2.51 (m, 1H), 2.45 (s, 3H), 3.59–3.78 (m, 2H), 4.98 (d, 1H, J = 10.5 Hz), 5.03 (d, 1H, J = 17.3 Hz), 5.70–5.85 (m, 1H).

A solution containing 145 mg (0.55 mmol) of **44** and 2 mg of rhodium(II) acetate dimer in 11 mL of benzene was heated at reflux for 20 min. The solvent was removed under reduced pressure and the residue was taken up in CH_2Cl_2 and filtered through a pad of Celite, and the solvent was removed under reduced pressure. The residue was subjected to flash chromatography to give 111 mg (86%) of 2-acetyl-2,3,5,6,7,7a,8,9,9a,-9b-decahydro-2,9b-epoxy-3-oxo-1*H*-cyclopenta[*ij*]quinolizine (**48**): mp 72–73 °C; IR ($CHCl_3$) 1730, 1450, 1355, 960 cm^{-1}; ^{1}H-NMR ($CDCl_3$, 300 MHz) δ 1.00–1.19 (m, 1H), 1.30–1.60 (m, 3H), 1.73 (m, 1H), 1.77 (m, 1H), 1.92-2.10 (m, 2H), 2.13 (d, 1H, J = 12.4 Hz), 2.15 (d, 1H, J = 12.4 Hz), 2.17–2.29 (m, 1H), 2.30–2.41 (m, 1H), 2.37 (s, 3H), 2.73 (dt, 1H, J = 12.4 and 3.7 Hz), 3.62–3.72 (m, 1H); ^{13}C-NMR ($CDCl_3$, 75 MHz) δ 21.7, 26.8, 28.7, 29.1, 31.2, 33.3, 35.0, 38.3, 43.9, 93.0, 102.5, 169.4, 200.3. Anal. Calcd for $C_{13}H_{17}NO_3$: C, 66.36; H, 7.28; N, 5.95. Found: C, 66.35; H, 7.30; N, 5.90.

Preparation and Rhodium(II)-Catalyzed Cycloaddition of 1-[2-Oxo-3-(but-3-enyl)azepinyl]-2-diazobutane-1,3-dione (45). A solution containing 1.0 g (8.85 mmol) of hexahydro-2*H*-azepin-2-one in 60 mL of dry THF was cooled to 0 °C under N_2. To this solution was added 10.31 mL (16.5 mmol) of a 1.60 M *n*-butyllithium solution in hexane. The resulting solution was stirred at 0 °C for 50 min and then 1.31 g (9.7 mmol) of 1-bromo-3-butene was added *via* syringe. The resulting solution was stirred at 0 °C for 10 min and then warmed to 15 °C for an additional 10 min. The reaction was quenched with a saturated NH_4Cl solution and the organic layer was separated. The aqueous layer was extracted with CH_2Cl_2 and the combined organic layer was dried over $MgSO_4$ and concentrated under reduced pressure. The residue was subjected to flash chromatography on a silica gel column to give 670 mg (45%) of 3-(but-3-enyl)azepin-2-one (**40**): mp 66–67 °C; IR ($CHCl_3$) 1660, 1370, 1115, 925 cm^{-1}; NMR ($CDCl_3$, 300 MHz) δ 1.22–1.82 (m, 6H), 1.83–2.00 (m, 2H), 2.02–2.20 (m, 2H), 2.30–2.48 (m, 1H), 3.05–3.37 (m, 2H), 4.92 (d, 1H, J = 10.7 Hz), 5.01 (d, 1H, J = 17.2 Hz), 5.70–5.90 (m, 1H), 6.00–6.30 (brs, 1H).

N-Acetoacetylation of the above compound in the standard manner gave 1-[2-oxo-3-(but-3-enyl)azepinyl]-2-diazobutane-1,3-dione as a clear oil (78%): IR (neat) 1720, 1695, 1395, 1190, 915 cm^{-1}; NMR ($CDCl_3$, 300 MHz) δ 1.23–1.63 (m, 4H), 1.65–1.81 (m, 1H), 1.82–1.97 (m, 3H), 1.98–2.13 (m, 2H), 2.23 (s, 3H), 2.66-2.78 (m, 1H), 3.18 (m, 1H), 3.88 (d, 1H, J = 16.2 Hz), 4.04 (d, 1H, J = 16.2 Hz) 4.65–4.80 (m, 1H), 4.92 (d, 1H, J = 5.5 Hz), 4.98 (d, 1H, J = 15.1 Hz), 5.66–5.85 (m, 1H).

Diazo transfer of the above compound gave 1-[2-oxo-3-(but-3-enyl)azepinyl]-2-diazobutane-1,3-dione (**45**) as a bright yellow oil (79%): IR (neat) 2140, 1730, 1695, 1255 cm^{-1}; NMR ($CDCl_3$, 300 MHz) δ 1.35–1.54 (m, 2H), 1.57–1.68 (m, 2H), 1.73–1.84 (m, 1H), 1.86–2.18 (m, 5H), 2.48 (s, 3H), 2.62–2.75 (m, 1H), 3.38–3.49 (m, 1H), 4.05–4.17 (m, 1H), 4.97 (d, 1H, J = 9.2 Hz), 5.02 (d, 1H, J = 18.8 Hz), 5.68–5.84 (m, 1H).

A solution containing 206 mg (0.74 mmol) of **45** and 2 mg of rhodium(II) acetate in 14 mL of benzene was heated at reflux for 1 h. The solvent was removed under reduced pressure and the residue was subjected to silica gel flash chromatography to give 75 mg (40%) of cycloadduct **49** as a clear oil: IR (neat) 1740, 1455, 1370, 1050, 810 cm^{-1}; NMR ($CDCl_3$, 300 MHz) δ 1.25–1.42 (m, 1H), 1.55–1.92 (m, 7H), 1.94–2.05 (m, 1H), 2.08–2.25 (m, 3H), 2.30–2.42 (m, 1H), 2.38 (s, 3H), 2.44–2.57 (m, 1H), 2.80–2.95 (m, 1H), 3.68–3.80 (m, 1H).

The second fraction contained 66 mg (36%) of 4-acetyl-4-hydroxy-2,2a,3,4,6,7,8,9-octahydro-1*H*-5a-azabenzo[*c,d*]azulen-5-one (**50**) as a white crystalline solid: mp 77–78 °C; IR ($CHCl_3$) 1720, 1640, 1360, 1210, 915 cm^{-1}; ^{1}H-NMR ($CDCl_3$, 300 MHz) 1.30–1.48 (m, 1H), 1.65 (t, 1H, J = 13.2 Hz), 1.66–1.90 (m, 4H), 1.92–2.08 (m, 1H), 2.10–2.30 (m, 4H), 2.25 (s, 3H), 2.35–2.50 (m, 1H), 2.84–3.00 (m, 1H), 3.32–3.45 (m, 1H), 4.33 (dt, 1H, J = 13.8 and 4.2 Hz), 4.62 (s, 1H); ^{13}C-NMR ($CDCl_3$, 300 MHz) δ 23.8, 25.4, 26.3, 27.0 28.0, 36.2, 36.7, 38.1, 45.4, 79.4, 121.2, 135.0, 168.4, 208.7. Anal. Calcd for $C_{14}H_{19}NO_3$: C, 67.45; H, 7.68; N, 5.62. Found: C, 67.64; H, 7.72; N, 5.65.

Preparation and Rhodium(II)-Catalyzed Cycloaddition of 1-[2-Oxo-3-(pent-4-enyl)piperidin-1-yl]-2-diazobutane-1,3-dione (46). A solution containing 1.50 g (15.1 mmol) of 2-piperidone in 75 mL of THF was cooled to 0 °C under N_2. To this solution was added 20 mL (32 mmol) of a 1.60 M *n*-butyllithium solution in hexane. The yellow solution was stirred for 1 h at 0 °C. A solution containing 2.68 g (18 mmol) of 5-bromo-1-pentene in 7 mL of THF was added *via* syringe. The resulting mixture was stirred for 1 h at 0 °C and then warmed to 25 °C and stirred for 1 h. At the end of this time the reaction was quenched with 10 mL of a saturated NH_4Cl solution. The organic layer was separated and the aqueous layer was extracted with CH_2Cl_2. The combined organic layer was washed with a saturated NaCl solution, dried over $MgSO_4$, and concentrated under reduced pressure. The residue was subjected to flash chromatography on a silica gel column to give 2.14 g (85%) of 3-(pent-4-enyl)-2-piperidone (**41**): mp 46–47 °C; IR ($CHCl_3$) 1655, 1455, 1310, 920 cm^{-1}; ^{1}H-NMR ($CDCl_3$, 300 MHz) δ 1.18–1.44 (m, 4H); 1.47–1.63 (m, 1H), 1.65–1.87 (m, 3H), 1.88–2.02 (m, 2H), 2.04–2.20 (m, 1H), 3.02–3.27 (m, 2H), 4.77 (d, 1H, J = 10.2 Hz), 4.87 (d, 1H, J = 17.0 Hz), 5.60–5.78 (m, 1H), 7.42 (brs, 1H); ^{13}C-NMR ($CDCl_3$, 75 MHz) δ 20.5, 25.4, 25.6, 30.5, 33.1, 40.1, 41.5, 113.7, 137.9, 174.8.

The above compound was subjected to the standard N-acetoacetylation conditions to give 1-[2-oxo-3-(pent-4-enyl)piperidin-1-yl]butane-1,3-dione (82%) as a yellow oil: IR (neat) 1730, 1360, 1270, 1155 cm^{-1}; ^{1}H-NMR ($CDCl_3$, 300 MHz) δ 1.25–1.50 (m, 4H), 1.65–1.88 (m, 3H), 1.90–2.06 (m, 3H), 2.18 (s, 3H), 2.38–2.42 (m, 1H), 3.51–3.65 (m, 1H), 3.75–3.92 (m, 1H), 3.89 (s, 2H), 4.87 (d, 1H, J = 11.7 Hz), 4.93 (d, 1H, J = 18.9 Hz), 5.64–5.80 (m, 1H); ^{13}C-NMR ($CDCl_3$, 75 MHz) δ 20.1, 24.5, 25.3, 29.0, 29.6, 32.8, 41.9, 42.3, 53.5, 113.7, 137.5, 168.0, 175.3, 200.2.

Diazo transfer of the above compound gave 1-[2-oxo-3-(pent-4-enyl)piperidin-1-yl]-2-diazobutane-1,3-dione (**46**) (90%) as a bright yellow oil: IR (neat) 2150, 1735, 1715, 750 cm^{-1}; ^{1}H-NMR ($CDCl_3$, 300 MHz) δ 1.28–1.58 (m, 4H), 1.67–2.09 (m, 6H), 2.30–2.45 (m, 1H), 2.35 (s, 3H), 3.50–3.70 (m, 2H), 4.85 (d, 1H, J = 10.4 Hz), 4.92 (d, 1H, J = 19.0 Hz), 5.60–5.80 (m, 1H); ^{13}C-NMR ($CDCl_3$, 75 MHz) δ 20.7, 25.4, 25.6, 28.0, 29.7, 33.0 42.6, 45.3, 81.7, 114.1, 137.6, 164.1, 174.6, 189.0.

A solution containing 99 mg (0.36 mmol) of **46** and 2 mg of rhodium(II) acetate dimer in 7 mL of benzene was heated at reflux for 25 min. The solvent was removed under reduced

pressure and the residue was subjected to flash chromatography to give 75 mg (84%) of 2-acetyl-2,3,6,7,7a,8,9,10,10a,10b-decahydro-2,10b-epoxy-3-oxo-1*H*,5*H*-benzo[*ij*]quinolizine (**52**) as a white solid: mp 85–86 °C; IR ($CHCl_3$) 1735, 1460, 1095 cm^{-1}; ^1H-NMR ($CDCl_3$, 300 MHz) δ 1.04–1.21 (m, 1H), 1.30–1.70 (m, 7H), 1.71–1.92 (m, 3H), 1.97–2.24 (m, 3H), 2.33 (s, 3H), 2.52–2.67 (m, 1H), 3.68–3.78 (m, 1H); ^{13}C-NMR ($CDCl_3$, 300 MHz) δ 19.1, 22.7, 25.9, 26.9, 27.1, 31.5, 33.9, 35.9, 37.3, 38.2, 89.9, 93.7, 169.7, 200.4. Anal. Calcd for $C_{14}H_{19}NO_3$: C, 67.45; H, 7.68; N, 5.62. Found: C, 67.29; H, 7.63; N, 5.67.

Preparation and Rhodium(II)-Catalyzed Cycloaddition of 1-[2-Oxo-6-(but-3-enyl)piperidin-1-yl]-2-diazobutane-1,3-dione (56). To a solution containing 315 mg (2.28 mmol) of 2-(3-butenyl)cyclopentanone[47] and 374 mg (4.56 mmol) of sodium acetate in 11 mL of methanol was added 317 mg (4.56 mmol) of hydroxylamine hydrochloride. The solution was stirred overnight at rt and was then diluted with 25 mL of ether and washed twice with a saturated solution of $NaHCO_3$. The aqueous layer was extracted with ether and the combined organic layer was washed with a saturated NaCl solution, dried over $NaHCO_3$, and concentrated under reduced pressure to give 297 mg (85%) of 2-(but-3-ene)cyclopentanone oxime (**53**): IR (neat) 1670, 910 cm^{-1}; NMR ($CDCl_3$, 90 MHz) δ 1.80–3.20 (m, 11H), 5.00–5.25 (m, 2H), 5.75–6.20 (m, 1H), 9.90 (brs, 1H).

To a solution containing 2.78 g (18.14 mmol) of the above oxime **53** in 300 mL of ether was added 4.15 g (19.95 mmol) of PCl_5 at 0 °C. The solution was allowed to warm to rt overnight and was then poured into an icy solution of 10 N NaOH. The reaction mixture was extracted with CH_2Cl_2 and the combined organic extracts were washed with a saturated NaCl solution, dried over $MgSO_4$, and concentrated under reduced pressure. The residue was subjected to flash silica gel chromatography to give 1.33 g (48%) of 6-(but-3-enyl)piperidin-2-one; IR (neat) 1670, 1455, 1350 cm^{-1}; NMR ($CDCl_3$, 300 MHz) δ 1.10–2.30 (m, 10H), 3.24-3.40 (m, 1H), 4.92 (d, 1H, J = 10.5 Hz), 4.98 (d, 1H, J = 18.0 Hz), 5.60–5.90 (m, 1H), 6.80 (brs, 1H); ^{13}C-NMR ($CDCl_3$, 75 MHz) δ 19.0, 27.4, 28.9, 30.7, 35.2, 51.8, 114.8, 136.8, 172.0.

N-Acetoacetylation of the above compound in the normal manner gave 1-[2-oxo-6-(but-3-enyl)piperidin-1-yl]butane-1,3-dione (29%): IR (neat) 1730, 1695, 1450, 910 cm^{-1}; NMR ($CDCl_3$, 300 MHz) δ 1.38–1.55 (m, 1H), 1.58–1.77 (m, 3H), 1.78–1.93 (m, 2H), 1.95–2.08 (m, 2H), 2.13 (s, 3H), 2.35–2.52 (m, 2H), 3.78 (d, 1H, J = 16.2 Hz), 3.88 (d, 1H, J = 16.2 Hz), 4.45–4.60 (m, 1H), 4.88 (d, 1H, J = 10.2 Hz), 4.95 (dd, 1H, J = 17.6 and 1.1 Hz), 5.62–5.80 (m, 1H); ^{13}C-NMR ($CDCl_3$, 75 MHz) δ 15.7, 24.0, 29.4, 29.4, 30.4, 33.1, 51.5, 53.9, 114.5, 136.7, 168.1, 173.3, 200.7.

Diazo transfer of the above compound gave 1-[2-oxo-6-(but-3-enyl)piperidin-1-yl]-2-diazobutane-1,3-dione (**56**) (88%): IR (neat) 2140, 1705, 1355, 920, 745 cm^{-1}; NMR ($CDCl_3$, 300 MHz) δ 1.47–1.62 (m, 1H), 1.70–2.20 (m, 7H), 2.43 (s, 3H), 2.47–2.65 (m, 2H), 4.23 (dd, 1H, J = 9.1 and 4.3 Hz), 4.96 (d, 1H, J = 10.3 Hz), 5.12 (d, 1H, J = 16.2 Hz), 5.64–5.90 (m, 1H).

A solution containing 77 mg (0.294 mmol) of **56** and 2 mg of rhodium(II) acetate in 6 mL of benzene was heated at reflux for 15 min. The solution was allowed to cool to rt and the solvent was removed under reduced pressure. The residue was subjected to flash chromatography to give 53 mg (76%) of 3-acetyl-3,9a-epoxy-1,6-ethano-1,3,4,6,7,8,9,9a-octahydro-4-oxo-2*H*-quinolizine (**58**): mp 103–104 °C; IR ($CHCl_3$) 1735, 1720, 1400, 1070 cm^{-1}; NMR ($CDCl_3$, 300 MHz) δ 1.33 (dd, 1H, J = 14.2 and 6.5 Hz), 1.58 (dd, 1H, J = 12.5 and 3.8 Hz), 1.67 (dd, 1H, J = 14.6 and 6.8 Hz), 1.72–2.43 (m, 9H), 2.33 (s, 3H), 2.45–2.57 (m, 1H), 4.16 (m, 1H); ^{13}C-NMR ($CDCl_3$, 75 MHz) δ 19.4, 20.7, 23.3, 26.8, 27.6, 27.9, 36.5, 41.6, 49.4, 90.2, 90.9, 172.8, 200.1. Anal. Calcd for $C_{13}H_{17}NO_3$: C, 66.36; H, 7.28; N, 5.95. Found: C, 66.29; H, 7.30; N, 5.94.

Preparation and Rhodium(II)-Catalyzed Cycloaddition of 1-[2-Oxo-5(but-3-enyl)pyrrolidin-1-yl]-2-diazobutane-1,3-dione (57). N-Acetoacetylation of 5-(but-3-enyl)pyrrolidin-2-one[51] (**55**) was accomplished using a procedure of Doyle's[52] to give 433 mg (37%) of 5-(3-butenyl)-*N*-(2-diazo-1,3-dioxobutyl)-2-pyrrolidinone (**57**): IR (neat) 2140, 1730, 970 cm^{-1}; NMR ($CDCl_3$, 300 MHz) δ 1.35–1.55 (m, 1H), 1.60–1.75 (m, 1H), 1.84–2.22 (m, 4H), 2.35 (s, 3H), 2.35–2.60 (m, 2H), 4.20–4.32 (m, 1H), 4.87 (d, 1H, J = 10.4 Hz), 4.93 (d, 1H, J = 17.5 Hz), 5.59–5.80 (m, 1H); ^{13}C-NMR ($CDCl_3$, 75 MHz) δ 22.7, 28.0, 28.4, 31.1, 31.8, 56.8, 80.8, 114.8, 136.3, 160.0, 174.0, 189.3.

A solution containing 44 mg (0.178 mmol) of **57** and 2 mg of rhodium(II) acetate in 3.5 mL of benzene was heated at reflux under N_2 for 6 h. At the end of this time the solvent was removed under reduced pressure and the residue was subjected to flash chromatography to give 27 mg (69%) of 6-acetyl-6,8a-epoxy-1,2,3,5,6,7,8,8a-octahydro-5-oxo-3,8-ethanoindolizine (**59**): mp 136–137 °C; IR ($CHCl_3$) 1735, 1719, 1455 cm^{-1}; NMR ($CDCl_3$, 300 MHz) δ 1.30–1.40 (m, 1H), 1.62–2.10 (m, 5H), 2.20–2.38 (m, 3H), 2.40 (s, 3H), 2.41–2.61 (m, 2H), 4.13 (d, 1H, J = 7.4 Hz); ^{13}C-NMR ($CDCl_3$, 75 MHz) δ 18.8, 23.5, 25.2, 26.7, 28.1, 35.0, 42.6, 49.5, 98.9, 99.0, 168.4, 199.5. Anal. Calcd for $C_{12}H_{15}NO_3$: C, 65.14; H, 6.83; N, 6.33. Found: C, 65.06; H, 6.86; N, 6.30.

2-Acetyl-2-hydroxy-2,5,6,7,8,9,10,10a-octahydro-1*H*-pyrido[3,2,1-*ij*]quinolin-3-one (61). To a solution containing 88 mg (0.354 mmol) of **52** in 5 mL of CH_2Cl_2 at −78 °C under N_2 was added 123 mg (1.06 mmol) of triethylsilane and 75 mg (0.53 mmol) of boron trifluoride etherate. The solution was stirred at −78 °C for 2.5 h and was then allowed to warm to rt. After stirring for 3.5 h at rt, the reaction mixture was quenched with 10 mL of a saturated $NaHCO_3$ solution. The resultant mixture was extracted with CH_2Cl_2 and the combined organic extracts were washed with a saturated NaCl solution, dried over $MgSO_4$, and concentrated under reduced pressure. The crude residue was subjected to flash silica gel chromatography to give 49 mg (56%) of 2-acetyl-2-hydroxy-2,5,6,7,8,9,10,10a-octahydro-1*H*-pyrido[3,2,1-*ij*]quinolin-3-one (**61**): IR (neat) 1710, 1624, 1101 cm^{-1}; NMR ($CDCl_3$, 300 MHz) δ 1.20–1.35 (m, 2H), 1.39–2.08 (m, 9H), 2.11 (dd, 1H, J = 13.1 and 3.8 Hz), 2.28 (s, 3H), 2.33–2.47 (m, 1H), 3.14–3.28 (m, 1H), 4.30 (dt, 1H, J = 13.0 and 4.4 Hz), 4.57 (s, 1H, exchanged D_2O); ^{13}C-NMR ($CDCl_3$, 75 MHz) δ 21.2, 21.5, 24.4, 27.6, 29.9, 30.1, 30.2, 36.1, 41.1, 79.1, 115.3, 130.0, 167.5, 208.9; HRMS calcd for $C_{14}H_{19}NO_3$: C, 67.43; H, 7.69; N, 5.62. Found: C, 67.19; H, 7.58; N, 5.35.

1-Benzyl-3-hydroxy-4-methyl-2-oxooctahydro-1-pyridine-3-carboxylic Acid Methyl Ester (62). To a solution of 0.10 g (0.32 mmol) of **26** in 5.0 mL of CH_2Cl_2 under Ar at −20 °C was added 0.15 g (1.29 mmol) of Et_3SiH. This mixture was treated with 0.09 g (0.65 mmol) of BF_3–Et_2O dropwise. The reaction mixture was slowly warmed to rt and stirred for 6 h. The reaction mixture was taken up in 50 mL of Et_2O and washed with saturated aqueous $NaHCO_3$, saturated aqueous NH_4Cl, and brine. The organic extract was dried over $MgSO_4$, filtered, and concentrated under reduced pressure. The residue was subjected to flash silica gel chromatography to give 95 mg (93%) of the bicyclic lactam **62** as a white solid: mp 96–97 °C; IR (neat) 3403, 2957, 1752, 1725, 1637 cm^{-1}; ^1H-NMR ($CDCl_3$, 300 MHz) δ 1.01 (d, 3H, J = 5.4 Hz), 1.44 (m, 3H), 1.72 (m, 1H), 1.95 (m, 2H), 2.18 (m, 2H), 3.57 (dt, 1H, J = 9.0 and 7.5 Hz), 3.75 (s, 3H), 4.39 (s, 1H), 4.71 (AB, 2H, J = 15.1 Hz, $\Delta\nu$ = 407.2 Hz), 7.38–7.20 (m, 5H); ^{13}C-NMR ($CDCl_3$, 75 MHz) δ 13.6, 22.3, 30.0, 32.0, 38.4, 39.1, 48.7, 52.4, 59.1, 77.6, 127.3, 127.7, 128.4, 136.3, 169.5, 170.7. Anal. Calcd for $C_{18}H_{23}NO_4$: C, 68.12; H, 7.30. Found: C, 68.15; H, 7.32.

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Supplementary Material Available: Copies of ^{13}C-NMR spectra (75 MHz) of compounds **25**, **29**, and **32** lacking analyses (3 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.

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