Indirect Electroreductive Cyclization of *N*-Allyl and *N*-Propargylamides Using a Nickel(II) Complex as an Electron-Transfer Catalyst: Selective Formation of Halogenated and Non-halogenated Pyrrolidinones

Shigeko Ozaki,* Hidenori Matsushita, Miho Emoto, and Hidenobu Ohmori

Faculty of Pharmaceutical Sciences, Osaka University, 1–6 Yamadaoka, Suita, Osaka 565, Japan.
Received July 25, 1994; accepted August 24, 1994

Nickel(II) complex-catalyzed indirect electroreduction of *N*-allyl and *N*-propargyl-α-bromoamides conducted in dimethylformamide with 2 eq of a hydrogen atom donor, diphenylphosphine, afforded the corresponding pyrrolidinones as the sole cyclized product in good yields, while that of *N*-allyl-α-iodoamides in acetonitrile gave the iodinated pyrrolidinones. Under both conditions the *trans*-C-3: C-4 pyrrolidinones were formed predominantly.

Keywords α-halogenoamide; radical cyclization; nickel(II) complex; catalytic electroreduction; pyrrolidinone

Radical cyclizations to form four or five-membered lactams (pyrrolidinones) have attracted much attention from both synthetic[1] and mechanistic[2] viewpoints. It is well known that net reduction of the carbamoyl radical always occurs along with cyclization to the corresponding lactam when the cyclization of a carbamoyl radical is attempted by the tin hydride method.[2a,c,d,f] The formation of the reduction products is explained as follows: the relatively slow cyclization of the carbamoyl radical caused by the high barrier to rotation[2g,3] cannot compete with hydrogen atom abstraction even at low tin hydride concentrations, unless the structure of the starting amide is very favorable for cyclization.[2f] The formation of pyrrolidinones *via* cyclization of carbamoyl radicals has recently been achieved by the halogen atom-transfer method using a ditin, hexabutylditin,[2g] or ruthenium complexes as catalysts.[4] The products from the halogen atom-transfer method are halogenated ones and are suitable for subsequent functionalization. However, further tin hydride reduction is required when the resulting halogen functionality is not desired.

We have shown that the electroreductive generation of alkyl and vinyl radicals from various halides using nickel(II) complexes as electron-transfer catalysts is a useful synthetic alternative to the tin hydride method.[5] In a previous paper,[5c] we have reported that a Ni(II) complex, Ni(II) (CR),[6] catalyzed indirect electroreduction of *N*-allyl- and *N*-propargyl-α-bromoamides, providing pyrrolidinone derivatives in good yield, and the relative yields of brominated to non-brominated pyrrolidinones depend on the ability of the solvent to donate a hydrogen atom to the radical. For example, the electrolysis of an α-bromoamide *N*-allyl-*N*-(bromoacetyl)toluene-*p*-sulfonamide in acetonitrile gave brominated and non-brominated pyrrolidinones in 33% and 8% yields, respectively, while that in dimethylformamide (DMF) provided brominated and non-brominated pyrrolidinones in 14% and 41% yields, respectively. The electrolysis of the same α-bromoamide in acetonitrile in the presence of 2 eq of a hydrogen atom donor, diphenylphosphine (Ph_2PH), produced a non-brominated pyrrolidinone as the sole cyclized product in 58% yield. These results suggest that the ability of DMF and acetonitrile to donate a hydrogen atom to radicals is insufficient, and in paticular, the ability of acetonitrile to donate a hydrogen atom is much lower than that of DMF, so that the major reaction in acetonitrile would proceed *via* bromine atom transfer.[7] Iodine atom transfer from an iodocarbonyl compound to alkyl radicals has been reported to be much faster than bromine atom transfer from the corresponding bromocarbonyl compound.[7a] These facts imply that the catalytic electroreduction of α-iodoamides in acetonitrile could afford iodinated pyrrolidinones selectively as the sole cyclized product.

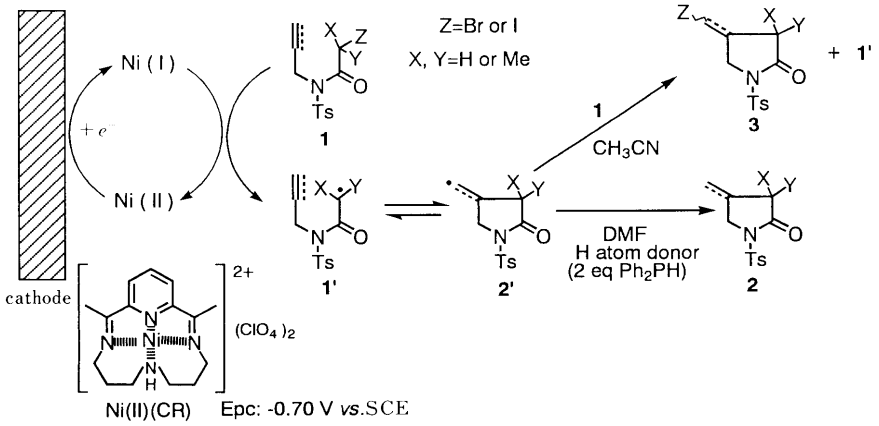


Chart 1

In the present paper, we wish to report that a nickel(II) complex-catalyzed electroreduction of α-halogenoamides can achieve the selective formation of halogenated and non-halogenated pyrrolidinones by making use of the difference in the ability of solvents to donate a hydrogen atom to the radical and the difference between the transfer rates of halogen from the α-iodoamide and α-bromoamide to the radical (**2′** in Chart 1).

Results and Discussion

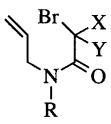
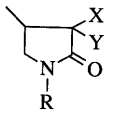
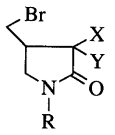
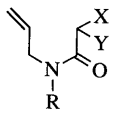
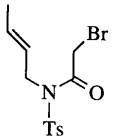
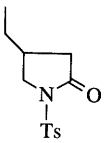
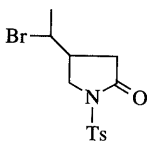
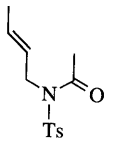
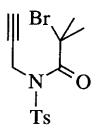
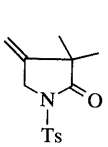
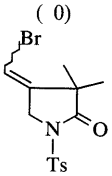
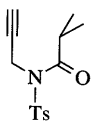
The iodoamides are more reducible than the corresponding bromides (Tables I, II) and the intermediate carbamoyl radicals (**1′**) are supposed to be more reducible than the iodoamides.[5b] In order to prevent further reduction of intermediate radicals (**1′**), we used nickel(II) (CR)$(ClO_4)_2$[6] again as a catalyst of electroreduction of α-halogenoamides, since the complex exhibits its Ni(I)/Ni(II) redox potential at the least negative potential among the complexes which show voltammograms indicating occurrence of an electron transfer from electroreductively generated nickel(I)$(CR)^+$ to the α-halogenoamides.[5b] The electrolysis to provide non-halogenated pyrrolidinones was carried out in DMF in the presence of 2 eq of a hydrogen atom donor, diphenylphosphine, using α-bromoamides as the starting amides, while that to give halogenated pyrrolidinones was done in acetonitrile using α-iodoamides as the starting amides. The electrolysis of α-halogenoamides was carried out in catholyte (20 ml) containing a supporting electrolyte (0.1 M Et_4NClO_4), the halogenoamide (1 mmol), a proton source (NH_4ClO_4 2 eq based on the amide), a catalytic amount of nickel(II) (CR) $(ClO_4)_2$ (0.2 eq based on the amide), and a hydrogen donor diphenylphosphine (2 eq based on the amide, only in the electrolysis to provide non-halogenated pyrrolidinones), potentiostatically at the cathodic peak potential of the nickel complex, −0.70 V *vs.* saturated calomel electrode (SCE) using a graphite plate as the cathode in a divided cell under an inert gas at room temperature. As shown in Table I, the reactions in DMF with 2 eq of Ph_2PH provided the non-brominated pyrrolidinones as the sole cyclized product.

The electroreduction of a bromomethylpyrrolidinone **3a** to a methylpyrrolidinone **2a** under the present conditions has already been ascertained not to occur.[5c] The yields of pyrrolidinones slightly increased in the order **2a**< **2b**<**2c**, *i.e.*, in the order of increase in stability of the intermediate carbamoyl radicals. The reaction of **1b** gave predominantly the thermodynamically more stable *trans*-C-3 : C-4 isomer (*trans* : *cis* = 87 : 13).

The results of the electroreduction of α-iodoamides in acetonitrile are summarized in Table II.

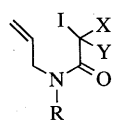
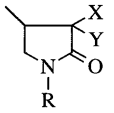
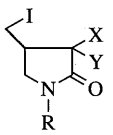
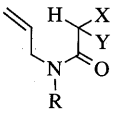
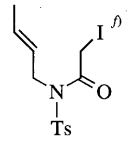
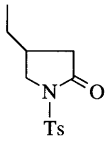
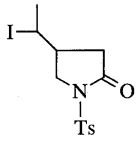
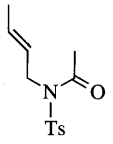
The α-iodoamides **1g—j** provided the respective iodinated pyrrolidinones **3(g—j)** as the sole cyclized product in good yields along with small amounts of re-

TABLE I. Ni(II)(CR)-Catalyzed Electroreductive Cyclization of α-Bromoamides in DMF in the Presence of Diphenylphosphine[a]

Substrate	F/mol[b]	Product[c] (Yield %)		
				
R = Ts,				
1a: X = Y = H		**2a**	**3a**	**4a**
Epc; −1.50 V[d]	0.72	(59)	(0)	(8)
in MeCN	0.66	(8)	(33)	
1b: X = H, Y = Me		**2b**	**3b**	**4b**
Epc; −1.49 V[d]	0.91	(64)[e]	(0)	(8)
1c: X = Y = Me		**2c**	**3c**	**4c**
Epc; −1.56 V[d]	0.75	(78)	Trace	Trace
R = allyl				
1d: X = Y = H		**2d**	**3d**	**4d**
Epc; −1.78 V[d]	0.87	(46)	(0)	(13)
				
1e		**3e**	**3e**	**4e**
Epc; −1.48 V[d]	0.74	(50)	(0)	(17)
				
1f		**2f**	**3f**	**4f**
Epc; −1.44 V[d]	1.02	(48)	Trace	(16)

a) For conditions, see text. *b*) Electricity consumed for the conversion of the substrate. *c*) Isolated yield based on the initial substrate. *d*) Cathodic peak potential of the substrate in V *vs.* SCE mesured in DMF measured in acetonitrile. *e*) Mixture of stereoisomers, *trans*/*cis* = 83/13.

TABLE II. Ni(II)(CR)-Catalyzed Electroreductive Cyclization of α-Iodoamides in Acetonitrile[a]

Substrate	F/mol[b]	Product[c] (Yield %)		
				
R=Ts,				
1g: X=Y=H		**2g**	**3g**	**4a**
Epc; −1.38 V[d]	0.87	(0)	(61)	(14)
1h: X=H, Y=Me		**2h**	**3h**	**4b**
Epc; −1.26 V[d]	0.95	(0)	(63)[e]	(7)
R=allyl				
1i: X=Y=H		**2i**	**3i**	**4i**
Epc; −1.48 V[d]	0.73	(0)	(70)	(10)
				
1j		**2j**	**3j**	**4j**
Epc; −1.17 V[d]	0.70	(0)	(41)	(15)

a) For conditions, see text. *b*) Electricity consumed for the conversion of the substrate. *c*) Isolated yield based on the initial substrate. *d*) Cathodic peak potential in V *vs.* SCE measured in DMF. *e*) *trans*-Isomer. *f*) Mixture of two rotamers, *anti*/*syn*=6/1.

duction products. Neither non-iodinated pyrrolidinones nor the products formed by coupling of the cyclized products (**2′** in Chart 1) were afforded, in contrast to the cyclizations of alkyl radicals or vinyl radicals performed by the same method.[5a,d] The pyrrolidinone **3h** was shown to be the *trans*-C-3 : C-4 isomer. The amounts of electricity consumed for the conversion of the iodoamides in acetonitrile seem to be considerably larger than anticipated based on the mechanism that **3g—j** would be formed through iodine atom transfer. The extra electricity might be consumed by further reduction of the intermediate carbamoyl radical **1′** to the simple reduction product and unidentified products before cyclization.[8] It seems likely that towards the end of electrolysis, a large part of **2′** might revert to the more stable and reducible carbamoyl radical **1′**,[8] since the concentration of iodoamides is no longer sufficient to transfer iodine to **2′**. The predominant or exclusive formation of *trans*-C-3: C-4-isomer, **2b** and **3h**, is contrary to the accepted generalization that *cis*-cyclization is predominant in 1,5-radical cyclization of 1-substituted hexenyl radicals, where the reaction proceeds under stereo-electronic control.[2i,9] Similar stereoselectivity in carbamoyl radical cyclizations has been reported by Ikeda *et al.*,[2c] and Parsons and Taylor,[1f] but the reason for preference of *trans*-product formation has not been established. Further work is needed to elucidate in what manner the substituents of the amide nitrogen, which seem to affect the barrier to rotation of the carbamoyl radical, influence the yield of the pyrrolidinone and the relative stereochemistry of C-3 and C-4.

In this work, we have demonstrated that a nickel(II) complex, nickel(II)(CR) can catalyze electroreduction of α-halogenoamides to achieve the selective formation of halogenated and non-halogenated pyrrolidinones by making use of the difference in the ability of the solvent to donate a hydrogen atom to the radical and the difference between the halogen transfer rates from the α-iodoamides and α-bromoamide to the radical (**2′** in Chart 1).

Experimental

Instrumentation NMR spectra were taken on a JEOL EX-270, JEOL GX-500 or Varian VXR-200 instrument. The *J*-values are given in hertz (Hz). IR spectra were taken on a JASCO A-202 instrument. Cyclic voltammetry was performed with a three-electrode system employing a linear scanning unit (Huso Electrochemical System HECS 321B) equipped with a potentiostat (Hokuto Denko PS-55B). Controlled-potential electrolysis was carried out with a potentiostat (Hokuto Denko HA 105S), and the quantity of electricity was recorded with a coulometer (Hokuto Denko HF-201).

Materials α-Bromoamides **1a**, **1c**, and **1d** were prepared as mentioned previously.[5c]

***N*-Allyl-*N*-(2-bromopropionyl)-*p*-toluenesulfonamide (1b)** *N*-Allyl-*N*-*p*-toluenesulfonamide (2.1 g, 10 mmol) in dry benzene (15 ml) and α-bromopropionyl bromide (4.3 g, 20 mmol) in dry benzene (15 ml) were successively added dropwise to NaH (0.8 g, 20 mmol; 60% in oil) in benzene (10 ml). After being stirred for 9 h at 50—60 °C under nitrogen the reaction mixture was diluted with 1 N aqueous NaOH (100 ml) and extracted with diethyl ether. Purification of the crude product by silica gel column chromatography yielded compound **1b** as a solid (3.0 g, 80%); mp 39—40 °C (*Anal.* Calcd for $C_{13}H_{16}BrNO_3S$: C, 45.09; H, 4.66; N, 4.05. Found: C, 45.07; H, 4.55; N, 4.05.) IR $\nu_{max}^{CHCl_3}$ cm^{-1}: 1705 (amide), 1360, 1170 (sulfonamide), 1650 (C=C). ^{1}H-NMR (200 MHz, $CDCl_3$) δ: 1.74 (3H, d, *J*=6.6, MeCH), 2.45 (3H, s, MeAr), 4.40 (1H, dd, *J*=16, 5.8, CHHN), 4.69 (1H, dd, *J*=16, 4.4, CHHN), 4.87 (1H, q, *J*=6.6, CHBr), 5.26 (1H, d, *J*=10, CHH=CH), 5.30 (1H, d, *J*=16, CHH=CH), 5.82—6.02 (1H, m, CH=CH_2), 7.34 (2H, d, *J*=8.4, ArH), 7.84 (2H, d, *J*=8.4, ArH).

***N*-(2-Butenyl)-*N*-(bromoacetyl)-*p*-toluenesulfonamide (1e)** The bromoamide was prepared in a same manner as described for **1a** using bromoacetyl chloride (1.75 g, 10.7 mmol), *N*-(2-butenyl)-*N*-*p*-toluenesulfonamide (1.5 g, 6.6 mmol) and NaH (0.32 g, 8.0 mmol; 60% in oil). Purification of the crude product by silica gel column chromatography yielded **1e** (0.95 g, 42%), mp 70—72 °C. IR $\nu_{max}^{CHCl_3}$ cm^{-1}: 1710 (amide). ^{1}H-NMR (200 MHz, $CDCl_3$) δ: 1.68 (3H, dd, *J*=6.2, 1, CH_3C=), 2,45 (3H, s, MeAr), 4.24 (2H, s, CH_2Br), 4.38 (2H, d, *J*=5.8, CH_2N), 5.52 (1H, m, CH=CH), 5.68 (1H, m, CH=CH), 7.35 (2H, d,

J=8.4, Ar H), 7.82 (2H, d, J=8.6, ArH).

***N*-Allyl-*N*-(iodoacetyl)-*p*-toluenesulfonamide (1g)** The α-iodoacetamide was prepared by halogen exchange reaction from *N*-allyl-*N*-(chloroacetyl)-*p*-toluenesulfonamide as described in the literature.[2g] Purification of the crude product by silica gel column chromatography gave **1g** as a solid, mp 53—53.5 °C (*Anal.* Calcd for $C_{12}H_{14}INO_3S$: C, 38.01; H, 3.72; N, 3.69. Found: C, 38.02; H, 3.71; N, 3.68.) IR $\nu_{max}^{CDCl_3}$ cm^{-1}: 1690 (amide), 1360, 1165 (sulfonamide). ^{1}H-NMR (200 MHz, $CDCl_3$) δ: 2.45 (3H, s, MeAr), 4.08 (2H, s, CH_2I), 4.46 (2H, d, J=5.1, CH_2N), 5.25—5.28 (2H, m, CH_2=CH), 5.76—5.98 (1H, m, CH=CH_2).

***N*-Allyl-*N*-(2-iodopropionyl)-*p*-toluenesulfonamide (1h)** *N*-Allyl-*p*-toluenesulfonamide (1.7 g, 8 mmol) in dry benzene (15 ml) and α-iodopropionyl chloride (5.5 g, 16 mmol) in dry benzene (10 ml) were successively added dropwise to NaH (1.3 g of 80% in oil, 43 mmol) in dry benzene (10 ml). After being stirred at 60 °C for 11.5 h under nitrogen the mixture was treated with 1 N aqueous NaOH and extracted with diethyl ether. Purification of the crude product by silica gel column chromatography yielded compound **1h** as a yellow oil (2.4 g, 76%), (*Anal.* Calcd for $C_{13}H_{16}INO_3S$: C, 39.70; H, 4.10; N, 3.56. Found: C, 39.97; H, 4.01; N, 3.54.) IR $\nu_{max}^{CDCl_3}$ cm^{-1}: 1700 (amide), 1360, 1165 (sulfonamide), 1645 (C=C). ^{1}H-NMR (200 Hz, $CDCl_3$) δ: 1.88 (3H, d, J=6.8, MeCH), 2.46 (3H, s, MeAr), 4.34 (1H, dd, J=16, 6.2, CHHN), 4.71 (1H, dd, J=16, 5.2, CHHN), 5.25—5.27 (2H, m, CH_2=CH), 5.82—6.04 (1H, m, CH=CH_2), 7.35 (1H, d, J=8.4, ArH)), 7.86 (1H, d, J=8.4, ArH).

N,*N*-Diallyliodoacetamide **1i** was prepared by halogen exchange reaction from *N*,*N*-diallylchloroacetamide in the same manner as described for **1g**. Purification of the crude product by silica gel column chromatography yielded **1i** as a reddish brown oil (2.16 g, 57% based on the chloroamide); ^{1}H-NMR (270 MHz, $CDCl_3$) δ : 3.68 (2H, s, CH_2I), 3.90 (2H, d, J=3.3, HHN), 3.93 (2H, d, J=8.3, HHN), 5.17 (4H, m, 2×CH_2=), 5.75 (2H, m, 2×CH=CH_2).

***N*-(But-2-enyl)-*N*-(iodoacetyl)-*p*-toluenesulfonamide (1j)** Compound **1j** was prepared by halogen exchange reaction from the corrresponding chloroacetyl chloride in the same manner as described for **1g**. Purification of the crude product by silica gel column chromatography afforded **1j** as a 6 : 1 mixture of two rotamers (5.72 g, 91% based on the chloride), mp. 63—66 °C; ^{1}H-NMR (270 MHz, $CDCl_3$) δ: assigned to the major rotamer 1.69 (3H, d, J=6.9, MeCH=), 2.45 (3H, s, MeAr) 4.08 (2H, s, ICH_2) 4.38 (2H, d, J=5.9, NCH_2), 7.35 (2H, d, J=8.6, ArH), 7.83 (2H, d, J=8.6); δ_H assigned to the minor rotamer 1.73 (3H, d, J=6.9, MeCH=), 2.45 (3H, s, MeAr), 4.11 (2H, s, ICH_2), 4.50 (2H, d, J=5.9, NCH_2), 7.35 (2H, d, J=8.6, ArH), 7.83 (2H, d, J=8.5, ArH).

2-Iodopropionyl chloride and 2-iodo-2-methylpropionyl chloride were prepared by the literature methods[10] and used without purification. Nickel(II) (CR) $(ClO_4)_2$ was prepared by the literature method.[11]

Controlled-Potential Electrolysis and Product Analysis The radical cyclizations of α-halogenoamides were carried out in DMF or MeCN (20 ml) containing a supporting electrolyte (0.1 M Et_4NClO_4), the halogenoamide (1 mmol), a proton source (NH_4ClO_4 2 eq based on the amide), a catalytic amount of nickel(II)(CR)$(ClO_4)_2$ (0.2 eq based on the amide), and a hydrogen donor, diphenylphosphine (2 eq based on the amide, only in the electrolysis to provide non-halogenated pyrrolidinones), potentiostatically at −0.70 V *vs.* SCE using a graphite plate as the cathode in a divided cell under an inert gas at room temperature. After all the amide had been consumed the catholyte was diluted with water. The products extracted with diethyl ether were separated by column chromatography (silica gel). Spectral data and analytical results of the products are as follows. Good elemental analyses for some iodinated products were not available because of their high sensitivity to light. 4-Methyl-1-tosylpyrrolidin-2-one **2a**, 3,3,4-trimethyl-1-tosylpyrrolidin-2-one **2c**, 3,3-dimethyl-4-methylene-1-tosylpyrrolidin-2-one **2f**, 4-bromomethyl-3,3-dimethyl-1-tosylpyrrolidin-2-one **3f**, *N*-acetyl-*N*-allyl-*p*-toluenesulfonamide **4a**, *N*-allyl-*N*-isobutyl-*p*-toluenesulfonamide **4c**, *N*,*N*-diallylacetamide **4d** and *N*-isobutyl-*N*-propargyl-toluene-*p*-sulfonamide **4f** showed spectral data and analytical results identical with those described in the previous paper.[5c]

3,4-Dimethyl-1-tosylpyrrolidin-2-one (2b) The crude product was chromatographed to give **4b** (21 mg, 8%) and **2b** as a mixture of *trans* and *cis* isomers (83 : 17) as judged from the integrated intensities of the MeAr protons in the ^{1}H-NMR spectra. The mixture of isomers was rechromatographed on silica gel to afford the *trans* isomer as a solid (152 mg, 57%) and the *cis* isomer (19 mg, 7%). The stereochemistry of **2b** has been tentatively assigned by a comparison of the ^{1}H-NMR spectra with those of structurally related compounds,[1d,2c] 3,4-dimethyl-1-phenylpyrrolidin-2-one **a** and octahydro-1,3-dimethylindol-2-one **b**. Two methyl groups in *cis*-C-3: C-4-**a** resonate at higher field than those in *trans*-C-3: C-4-**a** and the coupling constant between 3-H and 7a-H in (3*S**, −3a*S**, 7a*S**)-**b** is larger than that in (3*R**, −3a*S**, 7a*S**)-**b**. Nuclear Overhauser effect (NOE) difference spectroscopy was not informative since the resonance of H-3 and H-4 lie too close together.

trans-**2b**: A solid; mp 124—125 °C. (*Anal.* Calcd for $C_{13}H_{17}NO_3S$: C, 58.40; H, 6.41; N, 5.24. Found; C, 58.36; H, 6.26; N, 5.19.) IR $\nu_{max}^{CHCl_3}$ cm^{-1}: 1740 (lactam), 1365, 1170 (sulfonamide). ^{1}H-NMR (500 MHz, DMSO-d_6) δ : 0.97 (3H, d, J=7, MeCHCO), 1.04 (3H, d, J=7, MeCHCH$_2$), 1.95 (1H, m, MeCHCH$_2$), 2.15 (1H, dq, J=8.7, 7.3, MeCHCO), 2.41 (3H, s, MeAr), 3.28 (1H, t, J=9.6, 9.3, CHHN), 3.98 (1H, dd, J=9.6, 7.3, CHHN), 7.36 (2H, d, J=8.25, ArH), 7.83 (2H, d, J=8.25, ArH).

cis-**2b**: A solid; mp 88—89 °C. IR $\nu_{max}^{CHCl_3}$ cm^{-1}: 1740 (lactam), 1365, 1170 (sulfonamide). ^{1}H-NMR (500 MHz, DMSO-d_6) δ: 0.78 (3H, d, J=7.3, MeCHCO), 0.85 (3H, d, J=7.3, MeCHCH$_2$), 2.41 (3H, s, MeAr), 2.43 (1H, m, MeCHCH$_2$), 2.68 (1H, q, J=7.3, MeCHCO), 3.50 (1H, dd, J=9.6, 3.3, CHHCN), 3.89 (1H, dd, J=9.6, 6.0, CHHCN), 7.44 (2H, d, J=8.3, ArH), 7.82 (2H, d, J=8.3 Hz, ArH).

N-Allyl-*N*-propionyl-*p*-toluenesulfonamide (**4b**) Oil: IR $\nu_{max}^{CHCl_3}$ cm^{-1}: 1700, 1360, 1170 (sulfonamide), 1650 (C=C). ^{1}H-NMR (200 MHz, $CDCl_3$) δ : 1.04 (3H, t, J=7.3, CH_3CH_2), 2.44 (3H, s, MeAr), 2.57 (2H, q, J=7.4, CH_2CO), 4.49 (2H, d, J=8, CH_2N), 5.24—5.28 (2H, m, J=8, CH_2=CH), 5.80—6.00 (1H, m, CH=CH_2), 7.33 (2H, d, J=8.2 ArH), 7.82 (2H, d, J=8.2, ArH).

4-Ethyl-1-tosylpyrrolidinon-2-one (2e) A solid. mp 90—92 °C: (*Anal.* C, 58.66; H, 6.45; N, 5.16. Found: Calcd for $C_{13}H_{17}NO_3S$: C, 58.40, H, 6.41, N, 5.24 Found: C, 58.66: H, 6.45: N, 5.16). IR ν_{max}^{mull} cm^{-1}: 1740 (lactam), 1370, 1170 (sulfonamide). ^{1}H-NMR (270 MHz, $CDCl_3$) δ : 0.91 (3H, t, J=7.4, $MeCH_2$), 1.44 (2H, m, CH_2Me), 2.10 (1H, dd, J=16.7, 8.6, CHHCO), 2.26 (1H, m, CHCH$_2$Me), 2.44 (3H, s, MeAr), 2.55 (1H, dd, J=16.7, 7.8, CHCHCO), 3.45 (1H, dd, J=9.8, 7.1, CHCHN), 4.04 (1H, dd, J=9.8, 7.6, CHCHN), 7.34 (2H, d, J=7.9, ArH), 7.92 (2H, d, J=8.6, ArH).

***N*-(But-2-enyl)-*N*-acetyl-*p*-toluenesulfonamide (4e)** An oil. ^{1}H-NMR (270 MHz, $CDCl_3$) δ : 1.71 (3H, dd, J=3.6, I, CH_3CH=), 2.28 (3H, s, CH_3CO), 2.38 (3H, s, MeAr), 4.38 (2H, d, J=6.9, CH_2N), 5.5 (1H, m, CH=CH), 5.75 (1H, m, CH=CH), 7.32 (2H, d, J=7.9, ArH), 7.78 (2H, d, J=8.6, ArH).

4-Iodomethyl-1-tosylpyrrolidin-2-one (3g) A solid. mp 129.5—130 °C. (*Anal.* Calcd for $C_{12}H_{14}INO_3S$: C, 38.01; H, 3.72; N, 3.69. Found: C, 38.24; H, 3.67; N, 3.78). IR $\nu_{max}^{CHCl_3}$ cm^{-1}: 1735 (lactam), 1365, 1165 (sulfonamide). ^{1}H-NMR (200 MHz, $CDCl_3$) δ: 2.32 (1H, m, CH_2CHCH_2), 2.45 (3H, s, MeAr), 2.60 (2H, m, CH_2CO), 3.17 (2H, m, CH_2I), 3.58 (1H, dd, J=10.3, 5.8, CHHN), 4.09 (1H, dd, J=10.2, 7.2, CHHN), 7.35 (2H, d, J=7.9, ArH), 7.94 (2H, d, J=7.9, ArH).

The crude products from the electrolysis of **1h** were chromatographed on a silica gel column to afford **4b** (19 mg, 7%) and 4-iodomethyl-3-methyl-1-tosylpyrrolidin-2-one **3h**, as the sole stereoisomer. The stereochemistry of **3h** has been determined tentatively to be *trans* by comparison of its ^{1}H-NMR spectrum with those of the same compounds referred to in the case of **2b**. **3h** is a solid (248 mg, 63%); mp 150—151 °C. (*Anal.* Calcd for $C_{13}H_{16}INO_3S$: C, 39.70; H, 4.10; N, 3.56. Found: C, 40.52; H, 4.22, N, 3.50). IR $\nu_{max}^{CHCl_3}$ cm^{-1}: 1735 (lactam), 1365, 1170 (sulfonamide). ^{1}H-NMR (500 MHz, $CDCl_3$) δ: 1.16 (3H, d, J=6.8, CH_3), 2.07 (1H, m, CHCH$_2$), 2.23 (1H, dq, J=10.3, 6.8, CHCO), 2.44 (3H, s, MeAr), 3.10 (1H, dd, J=10.3, 8.6, CHHN), 3.38 (2H, m, CH_2I), 4.10 (1H, dd, J=10.3, 7.3, CHHN), 7.34 (2H, d, J=7.7 ArH), 7.93 (2H, d, J=8.6, ArH).

1-Allyl-4-iodomethylpyrrolidin-2-one (3i) A pale yellow oil. IR ν_{max}^{neat} cm^{-1}: 1690 (lactam). ^{1}H-NMR (270 MHz, $CDCl_3$) δ: 2.41 (1H, m, CHHCO), 2.61 (1H, m, CHHCO), 2.65 (1H, m, CHCH$_2$I), 3.08 (1H, dd, J=10.2, 3.9, CHHN), 3.25 (2H, m, ICH_2), 3.50 (1H, dd, J=10.2, 7.9, CHHN), 3.89 (2H, d, J=6.3, NCH_2CH=), 5.20 (2H, m, CH_2=), 5.72 (1H, m, CH=).

4-(1-Iodoethyl)-1-tosylpyrrolidin-2-one (3j) A solid. mp 118—121 °C. (*Anal.* Calcd for $C_{13}H_{16}INO_3S$: C, 39.70; H, 4.10; N, 3.56; I, 32.27; S, 7.97. Found: C, 40.70; H, 4.21; N, 3.55; I, 31.52; S, 7.97). ^{1}H-NMR (270 MHz, $CDCl_3$) δ : 1.87 (3H, d, J=6.60, CH_3), 2.24 (1H, dd, J=16.6, 9.2, CHHCO), 2.38 (1H, m, CH_2CHCH_2), 2.44 (3H, s, MeAr), 2.60 (1H, dd, J=16.6, 8.4, CHHCO), 3.53 (1H, dd, J=10.2, 7.9, HCl), 4.09 (2H, m, CH_2N), 7.34 (2H, d, J=7.9, ArH), 7.95 (2H, d, J=8.6,

ArH).

Acknowledgments We thank the Hayashi Memorial Foundation for Female Natural Scientists and the Ministry of Education, Science and Culture (Grant No. 06303010) for funding this work. We also thank Mr. K. Soh for experimental assistance.

References and Notes

1) *a*) H. Nagashima, K. Ara, H. Wakamatsu, K. Itoh, *J. Chem. Soc., Chem. Commun.*, **1985**, 518; *b*) K. Jones, M. Thompson, C. Wright, *ibid.*, 1986, 115; *c*) H. Ishibashi, T. S. So, K. Okochi, T. Sato, N. Nakamura, H. Nakatani, M. Ikeda, *J. Org. Chem.*, **56**, 95 (1991); *d*) T. Sato, N. Nakamura, K. Ikeda, M. Okada, H. Ishibashi, M. Ikeda, *J. Chem. Soc., Perkin Trans. 1*, **1992**, 2399; *e*) A. J. Clark, K. Jones, *Tetrahedron.*, **48**, 6875 (1992); *f*) A. F. Parsons, R. J. K. Taylor, *J. Chem. Soc., Chem. Commun.*, **1993**, 1224.

2) *a*) R. S. Jolly, T. Livinghouse, *J. Am. Chem. Soc.*, **110**, 7536 (1989); *b*) G. Stork, R. Mah, *Heterocycles*, **28**, 723 (1989); *c*) T. Sato, Y. Wada, M. Nishimoto, H. Ishibashi, M. Ikeda, *J. Chem. Soc., Perkin Trans. 1*, **1989**, 879; *d*) H. Nagashima, N. Ozaki, K. Seki, M. Ishii, K. Itoh, *J. Org. Chem.*, **54**, 4497 (1989); *e*) J. M. Clough, G. Pattenden, P. G. Wight, *Tetrahedron Lett.*, **30**, 7469 (1989); *f*) S. L. Fremont, J. L. Belletire, D. M. Ho, *ibid.*, **32**, 2335 (1991); *g*) D. P. Curran, J. Tamine, *J. Org. Chem.*, **56**, 2746 (1991); *h*) D. P. Curran, and N. C. DeMello, *J. Chem, Soc., Chem. Commun.*, **1993**, 1314; *i*) A. L. J. Beckwith, S. P. Joseph, R. T. A. Mayadunne, *J. Org. Chem.*, **58**, 4198 (1993).

3) W. E. Stewart, T. H. Siddall, III, *Chem. Rev.*, **70**, 517 (1970).

4) *a*) H. Nagashima, H. Wakamatsu, N. Ozaki, T. Ishii, M, Watanabe, T. Tajima, K. Itoh, *J. Org. Chem.*, **57**, 1682 (1992); *b*) H. Nagashima, N. Ozaki, M. Ishii, K. Seki, M. Washiyama, K. Itoh, *ibid.*, **58**, 464 (1993); *c*) H. Ishibashi, N. Uemura, H. Nakatani, M. Okazaki, T. Sato, N. Nakamura, M. Ikeda, *ibid.*, **58**, 2360 (1993).

5) *a*) S. Ozaki, H. Matsushita, H. Ohmori, *J. Chem. Soc., Chem. Commun.*, **1992**, 1120; *b*) *Idem, J. Chem. Soc., Perkin Trans. 1*, **1993**, 649; *c*) *Idem, ibid.*, **1993**, 2339; *d*) S. Ozaki, I. Horiguchi, H. Matsushita, H. Ohmori, *Tetrahedron Lett.*, **35**, 725 (1994).

6) Nickel(II) (CR) $(ClO_4)_2$: 2,12-dimethyl-3,7,11,17-tetraazabicyclo-[11.3.1]heptadeca-1(17),2,11,13,15-pentaenenickel(II)perchlorate, which shows the redox couple of Ni(I)/Ni(II) at around -0.7 V *vs.* SCE.

7) *a*) D. P. Curran, E. Bosch, J. Kaplan, M. Newcomb, *J. Org. Chem.*, **54**, 1826 (1989); *b*) D. P. Curran, *Synthesis*, **1988**, 489; *c*) D. P. Curran, M.-H. Chen, D. Kim, *J. Am. Chem. Soc.*, **111**, 6265 (1989).

8) It is suggested that stabilizing groups such as carbonyls can allow radical cyclizations to be reversible. M. Julia, *Acc. Chem. Res.*, **4**, 386 (1971); *idem, Pure Appl. Chem.*, **40**, 553 (1974).

9) A. L. J. Beckwith, *Tetrahedron*, **37**, 3073 (1981).

10) D. N. Harpp, L. Q. Bao, C. J. Black, J. G. Gleason, R. A. Smith, *J. Org. Chem.*, **40**, 3420 (1975).

11) J. L. Karn, D. H. Busch, *Inorg. Chem.*, **8**, 1149 (1969).