Study of the Regiochemistry and Stereochemistry of the [3 + 2] Cycloaddition between Nonstabilized Azomethine Ylides Generated from Tertiary Amine *N*-Oxides and Various Dipolarophiles

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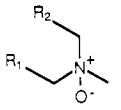
Kinetically formed nonstabilized azomethine ylides generated from tertiary amine *N*-oxides **1a–c** add to unactivated dipolarophile alkenes **10**, **12**, and **17**, alkynes **13** and **16**, benzothiophenone (**14**), and imine **15** to afford the corresponding heterocycles in good yields. The *stereochemistry* and *regiochemistry* of the cycloaddition are studied.

1,3-Dipolar cycloaddition of azomethine ylides to various dipolarophiles has been found to be useful for the preparation of a wide range of heterocycles.[1] Particular interest has been focused on the generation and reactions of ylides devoid of a stabilizing electron-withdrawing group.[2]

We have recently reported that LDA deprotonation of readily available amine *N*-oxides gives rise to ylides[3] that appear to be much more reactive than those structurally related dipoles generated either by desilylation of α-silyl iminium salts[2a] or by decarboxylation of imines of α-amino acids,[2b] since they can be trapped with a wide range of unactivated dipolarophiles. We have shown that trimethylamine *N*-oxide treated with LDA adds to alkenes, alkynes, imine, and thione double bonds to yield respectively pyrrolidines, pyrrolines, pyrroles, imidazolidines, and thiazolidines.[3c]

We now report the behavior of compounds **1a–c** in order to determine (i) *the deprotonation regiochemistry* of the *N*-oxides and of the resulting immonium salts I yielding ylides Y and (ii) *the stereo- and regiochemistry* of the cycloaddition between those ylides and various dipolarophiles.



1a $R_1 = H$; $R_2 = Me$

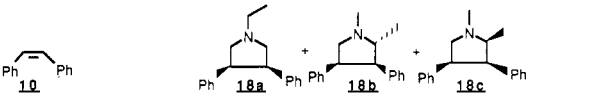
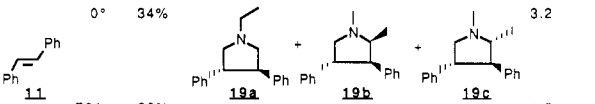
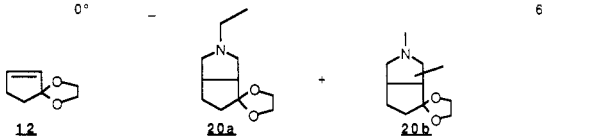
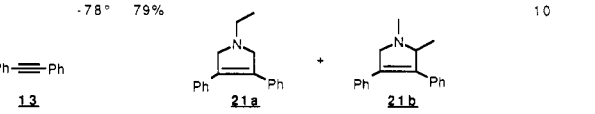
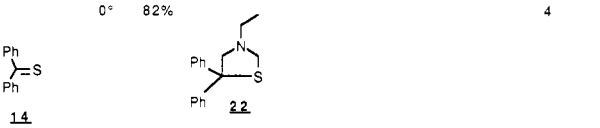
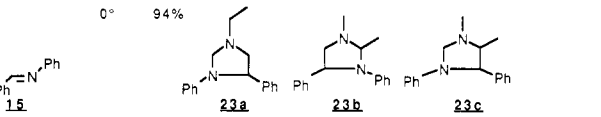
1b $R_1 = R_2 = Me$

1c $R_1, R_2 = (CH_2)_3$

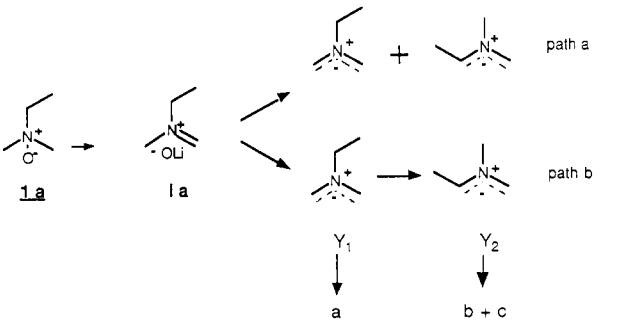
Results and Discussion

Deprotonation Regiochemistry. (a) Dimethylethylamine *N*-Oxide (1a). The results obtained by treating dimethylethylamine *N*-oxide (**1a**) with LDA in the presence of various dipolarophiles **10–15** are summarized in Table I. Kinetic deprotonation of the *N*-oxide **1a** occurs on the methyl group, leading to the immonium salt Ia (Scheme I). The exclusive deprotonation on this site is due to the more acidic character of the methyl protons.

Table I. Reaction between 1a and Various Dipolarophiles

entry	t°	Yield	a/b+c
			
1	-78°	23%	5.6
2	0°	34%	3.2
			
3	-78°	82%	4.5
4	0°	–	4.5
5	0°	–	6
			
6	-78°	79%	10
			
7	0°	82%	4
			
8	0°	94%	
			
9	0°	62%	5.6
10	-78°	25%	2.1

Scheme I



This result is in accordance with the fact that compounds **2** and **3**, which have no methyl group, can be deprotonated only by *t*-BuLi,[3d] while benzylic *N*-oxide **4** is deprotonated with lithium amide.[3a] It must be kept in mind that easily obtained benzylic ylides are stabilized and do not undergo

(1) Lown, J. W. In *1,3-Dipolar Cycloaddition Chemistry (General Heterocyclic Chemistry Series)*; Padwa, A., Ed.; Wiley-Interscience: New York, 1984; Vol. I, p 653.

(2) (a) Vedejs, E.; West, F. G. *Chem. Rev.* **1986**, *86*, 941 and reference, therein. (b) Grigg R.; Thianpatanagul, S. *J. Chem. Soc. Chem. Commun.* **1984**, 180. (c) Confalone, P. N.; Huie, E. M. *J. Am. Chem. Soc.* **1984**, *106*, 7175. (d) Joucla, M.; Mortier, J. *J. Chem. Soc., Chem. Commun.* **1985**, 1566.

(3) (a) Beugelmans, R.; Benadjilla-Iguertsira, L.; Chastanet, J.; Negron, G.; Roussi, G. *Can. J. Chem.* **1985**, *63*, 725. (b) Chastanet, J.; Roussi, G. *J. Org. Chem.* **1985**, *50*, 2910. (c) Beugelmans, R.; Chastanet, J.; Roussi, G. *Heteroccles* **1987**, *26*, 3197. (d) Roussi, G., unpublished results.

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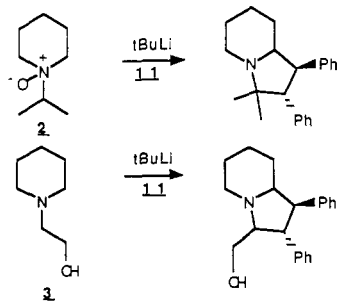
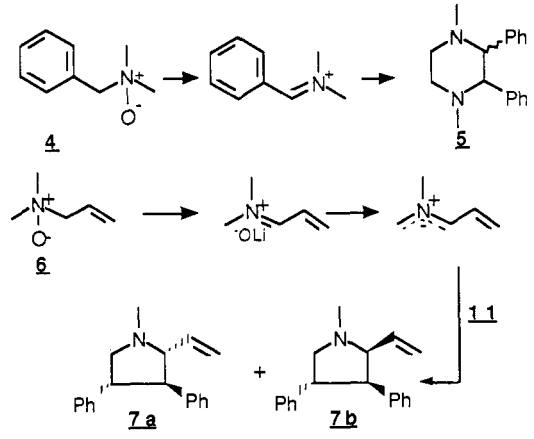
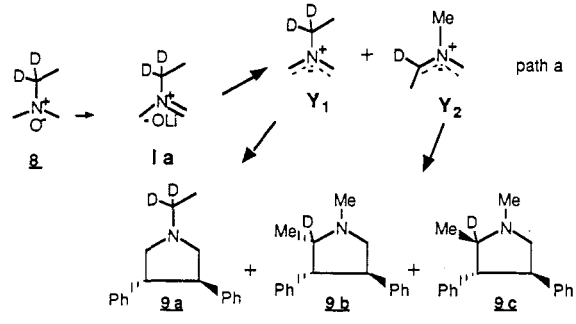


cycloaddition but duplicate to give head-to-head piperazines **5**.[3a] In the same manner, a conjugated entity generated by deprotonation of dimethylallylamine *N*-oxide (**6**) adds only to *trans*-stilbene (**11**) to yield pyrrolidines **7a,b** (**7a**/**7b** = 10) bearing a vinyl group in the 2-positions.



The mixture of the isomers **a** and **b** + **c** results from trapping of each ylide Y_1 and Y_2 generated either by initial differential deprotonation of immonium salt Ia (path a) or by equilibration (path b) (Scheme I).

The enhanced selectivity observed by using congested base (LiTMP) in the reaction with **11** (entry 5) and the formation of monodeuteriated pyrrolidines **9b,c** when reacting dideuteriated *N*-oxide **8** are in complete agreement with selective deprotonation (path a). (We acknowledge one of the referees for suggesting that we carry out these complementary experiments).



cis-Pyrrolidines are formed in low yield by cycloaddition to *cis*-stilbene (**10**), which appears to be about 20 times less reactive than trans isomer **11** as measured by competitive reactions. This result is in agreement with the known dipolarophilicity order observed in cycloaddition reactions.[4] A stereospecific reaction of thiobenzophenone (**14**) with Y_1 takes place to afford diphenylthiazolidine (**22**) (94%),

(4) Huisgen, R. In *1,3-Dipolar Cycloaddition Chemistry (General Heterocyclic Chemistry Series)*; Padwa, A., Ed.; Wiley-Interscience: New York, 1984; Vol. I, p 1.

Scheme II

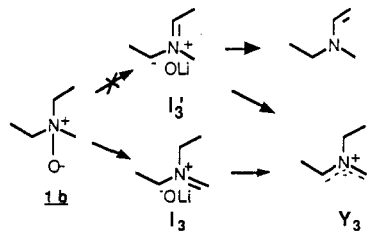
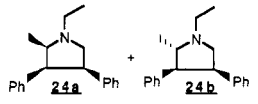
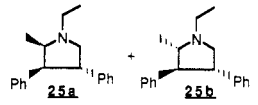
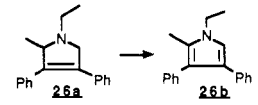
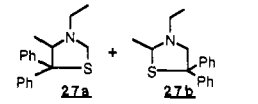
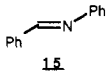
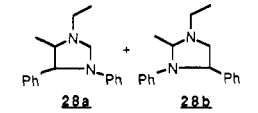
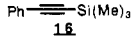
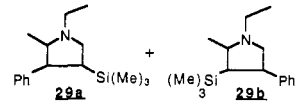
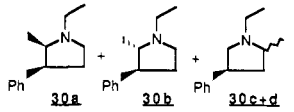


Table II. Reaction between 1b and Various Dipolarophiles

entry		t°C	Yield		a/b
1	 10	0°	41 %	 24a 24b	0.1
2	 11	0°	80%	 25a 25b	0.5
3	 13	-78°	39%	 26a 26b	
4	 14	0°	31%	 27a 27b	1.6
5	 15	0°	65%	 28a 28b	0.1
6	 16	0°	76%	 29a 29b	0.25
7	 17	0°	74%	 30a 30b 30c+d	a/b+c+d=1.2
8		-78°	66%		a+b/c+d=2.1

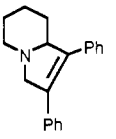
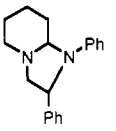
in agreement with the C=S bond dipolarophilicity.

The yields of these reactions are temperature dependent but the variations of selectivity are meaningless because of the low yields obtained at low temperature (entries 1 and 10).

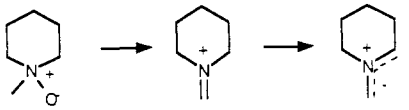
(b) Diethylmethylamine *N*-Oxide (1b). The heterocycles obtained by treating diethylmethylamine *N*-oxide (**1b**) with LDA in the presence of dipolarophiles carry an *N*-ethyl substituent. They arise from cycloaddition of the ylide Y_3 generated via the immonium salt I_3, kinetically formed by initial deprotonation of the *N*-oxide methyl group, rather than from I_3', which would have competitively been depronated toward enamine (Scheme II).

Table II summarizes the results obtained. The temperature can be responsible for the low yield of pyrroline **26a** (entry 3) as compared with that of the reaction carried out with silylated phenylacetylene, which affords **29** in much higher yield (76%, entry 6). (Phenylacetylene was silylated prior to reaction in order to prevent the generation of a high-energy LUMO anion, unable to be trapped by azomethine ylide.[4]) The thiazolidines **27** were isolated in low yield (entry 4) because they decomposed during TLC purification. The lability of such heterocycles is documented.[5] The cycloaddition of Y_3 to styrene yields

Table III. Reaction between 1c and Various Dipolarophiles

	t°C	Yield	
Ph≡Ph (13)	0°	66%	 (31)
 (15)	-78°	71%	 (32)

Scheme III



1c I_4 Y_4

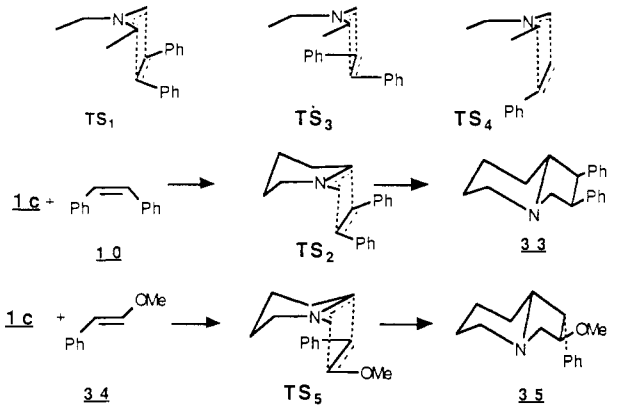
four isomers **30a–d**, in which **30a** is the major one (**a**/(**b** + **c** + **d**) = 0.8, entry 7).

(c) Methylpiperidine *N*-Oxide (1c). Table III summarizes the results obtained. Pyrroline **31** (66%) and imidazolidine **32** (71%) result from trapping of the ylide Y_4 by diphenylacetylene **13** and benzalaniline **15**, respectively. The methyl group is first deprotonated again, leading to the immonium salt I_4, the precursor of Y_4 (Scheme III).

Stereochemistry of the Cycloaddition. Pyrrolidine **24b** is formed selectively from *cis*-stilbene (**24a**/**24b** = 0.1). The stereoselectivity can be due to the exo transition state TS_1, by analogy with TS_2, which was proposed to explain the stereospecific formation of *exo*-indolizidine **33** from methylpiperidine *N*-oxide (**1c**) (Scheme III).[3b] Attractive secondary orbital interactions between the lone-pair nitrogen and the phenyl nucleus are unable to offset the repulsive van der Waals interactions in the endo transition state.[4] The decrease of stereoselectivity observed with *trans*-stilbene (**25a**/**25b** = 0.5) is due to the fact that there is an endo phenyl group, whatever the transition state involved. The favored isomer results from transition state TS_3 in which phenyl and methyl groups are trans (Scheme IV). The predominant formation of the cis isomer **30a** in the course of the reaction between diethylmethylamine *N*-oxide (**1b**) and styrene (**17**) results from a preferred endo transition state TS_4, stabilized by attractive secondary orbital interactions. The high *stereoselectivity* previously observed in the course of the reaction between methylpiperidine *N*-oxide (**1c**) and β-methoxystyrene (**34**), affording **35**, results also from a such stabilized transition state TS_5.

Regiochemistry of the Cycloaddition. In the hands of Bastide[6] and Houk[7] FMO theory has been successfully applied to explain the regiochemistry of 1,3-dipolar cycloadditions. The favored regioisomer will be the one formed through the transition state in which atoms with larger coefficients overlap. Due to the ambivalence of the dipolar termini, close values of their atomic coefficients

Scheme IV



TS_1 TS_3 TS_4

1c + 10 → TS_2 → 33

1c + 34 → TS_5 → 35

and resulting low selectivity are expected for nonstabilized ylides. For alkene dipolarophiles the frontier orbitals have the largest coefficients at the unsubstituted extremity on both the HOMO and LUMO.

The *stereoselective* formation of **30a** (**a**/(**b** + **c** + **d**) = 1.2) is in accord with the largest coefficient on the CH_2 terminus of the dipole as deduced from the preferred transition state TS_4 (Scheme IV). Bianchi[8] has pointed out that the end of the dipole with the greatest coefficient in the HOMO may be considered more nucleophilic than the other.

It can be seen that the *regiochemistry* of the cycloaddition between the ylides generated from amine *N*-oxide **1b** and the silylated phenylacetylene **16** or benzalaniline **15** leading respectively to **29** (**29a**/**29b** = 0.25) or **28** (**28a**/**28b** = 0.1) is consistent with a nucleophilic attack of the CH_2 terminus of the dipole at the more electrophilic end of the dipolarophile. The direction of the regiospecific addition of methylpiperidine *N*-oxide (**1c**) with **15** yielding **32** (71%) or with **34** yielding **35** (61%) suffers the same explanation.

The *stereo-* and *regiochemistry* of the addition of nonstabilized azomethine ylides generated from amine *N*-oxides **1a–c** can be explained by the classical scheme of the [3 + 2] dipolar cycloadditions. The most important feature is their ability to add to *unactivated* dipolarophiles, in contrast with the structurally related species generated by other ways which appear to be no more reactive than stabilized ylides.[2] The difference can be accounted for by the fact that dipoles generated by desilylation could undergo complexation by silicon,[2a] while deprotonation of amine *N*-oxides implies Li_2O elimination, which clearly does not interfere with the ylides Y.

It seems reasonable to expect that these new highly reactive species could be used for synthesis of natural products, and we are currently exploring this direction.

Experimental Section

General. Uncorrected melting points were measured on a Reichert melting point apparatus. Low-resolution mass spectra (MS) were obtained on an AEI M50 spectrometer, and exact masses (HRMS) were determined by high-resolution mass spectroscopy on a Kratos M50. ^1H NMR spectra (in $CDCl_3$) were recorded on Perkin-Elmer R12 (60 MHz), Bruker WP-200-54 (200 MHz), and Bruker WM-400 (400 MHz) spectrometers. Chemical shifts from TMS are given in δ. Purifications were achieved by column chromatography, preparative thin-layer chromatography (TLC, elution), or HPLC.

(5) Witek, J.; Bielawska, A.; Bielawski, J. *Heterocycles* **1980**, *14*, 1313. Lambert, J. B.; Majchrzak, M. W. *J. Am. Chem. Soc.* **1980**, *102*, 3588.
(6) Bastide, J.; Henri-Rousseau, O. *Bull. Soc. Chim. Fr.* **1973**, 2294.
(7) Houk, K. N.,; Yamaguchi, K. In *1,3-Dipolar Cycloaddition Chemistry (General Heterocyclic Chemistry Series)*; Padwa, A., Ed.; Wiley-Interscience: New York, 1984; Vol. II, p 407.
(8) Bianchi, G.; De Micheli, C.; Gandolfi, R. In *1,3-Dipolar Cycloaddition Involving X=Y Groups. The Chemistry of Double Bonded Functional Groups, Part I*; Patai, S., Ed.; Wiley-Interscience: New York, 1977; Chapter 6, p 369.

Materials. Amine *N*-oxide **1a–c** were prepared by H_2O_2 oxidation of the corresponding amines. Thiobenzophenone (**14**),[9] benzalaniline (**15**),[10] and 1-phenyl-2-(trimethylsilyl)acetylene (**16**)[11] were prepared by standard literature procedures.

General Procedure. The amine *N*-oxide (1 equiv) was dried just before use by heating under vacuum at 30 °C in a three-neck flask for 1 h. The dipolarophile (1.1 equiv) and anhydrous THF (50 mL) were then added with a syringe through a rubber septum under stirring, and the suspension was cooled at the chosen temperature (either 0 or −78 °C) before LDA (3.5 equiv) was introduced. The reaction was monitored by vapor phase (VPC) and thin-layer chromatography.

1-Methyl-2α-vinyl-3β,4α-diphenylpyrrolidine (7a) and 1-Methyl-2β-vinyl-3β,4α-diphenylpyrrolidine (7b). *N*-Oxide **6** (0.202 g, 2.0 mmol) and *trans*-stilbene (**11**) (0.360 g, 2 mmol) were treated with LDA at 0 °C for 3 h. A crude mixture (0.59 g) was obtained after workup. VPC analysis revealed the presence of **7a** and **7b** in a 10/1 ratio. Preparative TLC (CH_2Cl_2–MeOH (95/5) afforded **7a** (0.09 g, 0.34 mmol, 17%) and **7b** (0.037 g, 0.14 mmol, 7%): MS *m/e* 263, 83; ^{1}H NMR (400 MHz) δ 2.89 (s, 3 H), 2.93 (dd, 1 H, $H_{2\beta}$, $J_{H2\beta,3\alpha}$ = 9.5 Hz), 2.99 (dd, 1 H, $H_{5\alpha}$), 3.09 (dd, 1 H, $H_{3\alpha}$), 3.38 (m, 2 H, $H_{4\beta}$, $H_{5\alpha}$), 4.9–5.16 (2 dd, 2 H), 5.76 (m, 1 H), 7.1–7.4 (m, 10 H).

1-(1,1-Dideuterioethyl)-*trans*-3,4-diphenylpyrrolidine (9a) and 1,2-Dimethyl-2-deuterio-*trans*-3,4-diphenylpyrrolidines (9b,c). *N*-Oxide **8** (0.17 g, 1.86 mmol) and *trans*-stilbene (**11**) (0.38 g, 2.1 mmol) were treated with LDA at 0 °C for 5 h. A crude mixture (0.57 g) was obtained after extraction. VPC analysis revealed the presence of the three isomers **9a–c** in 8:1:0.5 ratio. Column chromatography yielded **9a,c** (0.253 g, 1 mmol, 53%). HPLC allowed the separation of the three isomers. **9a**: MS *m/e* 253, 238, 73; ^{1}H NMR (200 MHz) δ 1.12 (s, 3 H), 2.84 (m, 2 H), 3.13 (m, 2 H), 3.3 (m, 2 H), 7.19 (m, 10 H). **9b**: MS *m/e* 252, 237, 72; ^{1}H NMR (200 MHz) δ 0.73 (s, 3 H), 2.41 (s, 3 H), 2.51 (dd, 1 H), 3.4 (d, 1 H, J_{H_2,H_3} = 8 Hz), 3.56 (m, 2 H), 7.4 (m, 10 H). **9c**: MS *m/e* 252, 237, 72.

1-Ethyl-*cis*-3,4-diphenylpyrrolidine (18a) and 1,2α- and 1,2β-Dimethyl-3β,4β-diphenylpyrrolidine (18b,c). *N*-Oxide **1a** (0.178 g, 2 mmol) and *cis*-stilbene (**10**) (0.396 g, 2.2 mmol) were treated with LDA at 0 °C for 2 h. A crude mixture (0.68 g) was obtained after extraction. VPC analysis revealed the presence of the three isomers **18a** and **18b,c** in a 3.6 ratio. Preparative TLC purification (CH_2Cl_2–MeOH (92/8)) yielded **18a** containing **18c** (8%) (0.171 g, 0.68 mmol, 34%): MS *m/e* 251, 236, 71; ^{1}H NMR (400 MHz) δ 1.23 (t, 3 H, *J* = 7 Hz), 2.77 (q, 2 H), 3.02 (m, 2 H), 3.33 (m, 2 H), 3.83 (m, 2 H), 6.80–7.30 (m, 10 H). Picrate: mp 128–130 °C (EtOH). Anal. Calcd for $C_{18}H_{21}N$: C, 60.00; H, 5.00. Found: C, 59.54; H, 4.90. **11a**: ^{1}H NMR δ 1.19 (d, 3 H), 2.55 (s, 3 H).

A doublet centered at 0.73 ppm reveals traces of **18c**.

The same reaction performed at −78 °C involving the same quantities of starting products afforded after 3 h 0.458 g of a crude mixture containing **18a** and **18b,c** in a 5.6 ratio. TLC purification yielded **18a** (0.116 g, 0.6 mmol, 23%) containing traces of **18b**.

1-Ethyl-*trans*-3,4-diphenylpyrrolidine (19a) and 1,2-Dimethyl-*trans*-3,4-diphenylpyrrolidine (19b,c). *N*-Oxide **1a** (0.33 g, 3.7 mmol) and *trans*-stilbene (**11**) (0.734 g, 4.07 mmol) were treated with LDA at −78 °C for 3 h. A crude mixture (1.0 g) was obtained after extraction. VPC analysis revealed the presence of the three isomers **19a** and **19b,c** in a 4.5 ratio. Column chromatography afforded **19a–c** (0.77 g, 3.07 mmol, 82%). HPLC allowed the separation of the three isomers. **19a**: MS *m/e* 251, 236, 149, 91, 71; ^{1}H NMR (200 MHz) δ 1.2 (t, 3 H, *J* = 7 Hz), 2.6 (m, 2 H), 2.9 (m, 2 H), 3.2 (m, 2 H), 3.4 (m, 2 H), 7.3 (m, 10 H). Picrate: mp 157 °C (EtOH). Anal. Calcd for $C_{24}H_{24}N_4O_7$: C, 60.00; H, 5.00; N, 11.66; O, 23.33. Found: C, 60.15; H, 5.10; N, 11.79; O, 23.27. **19b**: MS *m/e* 251, 236, 91, 71; ^{1}H NMR (200 MHz) δ 0.83 (d, 3 H), 2.56 (s, 3 H), 2.72 (m, 1 H), 3.07 (m, 1 H), 3.66 (m, 3 H), 7.33 (m, 10 H). **12c**: ^{1}H NMR (200 MHz) δ 1.13 (d, 3 H), 2.47 (s, 3 H).

The reaction performed at 0 °C was simply monitored by VPC, which revealed, the same value for the **19a**/(**19b** + **19c**) ratio (4.5).

1-Ethyl-4,4-(ethylenedioxy)cyclopentano[*c*]pyrrolidine (20a,b). *N*-Oxide **1a** (0.32 g, 3.59 mmol) and **12** (0.48 g, 3.96 mmol) were treated with LDA at −78 °C for 3 h. A crude mixture (0.75 g) was obtained after workup. VPC analysis revealed the presence of 8% of a minor isomer **20b**. Column chromatography yielded **20a** (0.56 g, 2.84 mmol, 79%): MS *m/e* 197, 182, 152, 71; ^{1}H NMR (60 MHz) δ 1.1–1.6 (m, t, 5 H), 1.6–2.1 (m, 4 H), 2.1–3 (m, 6 H), 3.9 (s, 4 H). Picrate: mp 122 °C (EtOH). Anal. Calcd for $C_{17}H_{22}N_4O_9$: C, 47.88; H, 5.16; N, 13.14, O, 33.80. Found: C, 47.52; H, 5.11; N, 13.26; O, 33.70.

1-Ethyl-3,4-diphenyl-2,5-dihydropyrrole (21a) and 1,2-Dimethyl-3,4-diphenyl-2,5-dihydropyrrole (21b). *N*-Oxide **1a** (0.178 g, 2 mmol) and diphenylacetylene (**13**) (0.356 g, 2 mmol) were treated with LDA at 0 °C for 5 h. A crude mixture (0.52 g) was obtained after extraction. VPC analysis revealed the presence of the two isomers **21a,b** (**21a**/**21b** = 4). A first purification on preparative TLC (ether) yielded **21a** (0.41 g, 1.65 mmol, 82%) containing 20% of **21b**. Further TLC purification afforded the two isomers. **21a**: MS *m/e* 249, 234, 172; ^{1}H NMR (200 MHz) δ 1.22 (t, 3 H), 2.80 (q, 2 H), 3.99 (s, 4 H), 7–7.6 (m, 10 H). Picrate: oil. Anal. Calcd for $C_{18}H_{19}N$: C, 86.75; H, 7.63. Found: C, 86.54; H, 7.69. **21b**: ^{1}H NMR (200 MHz) δ 1.14 (d, 3 H), 2.55 (s, 3 H), 3.63 (m, 1 H), 3.9 (q, 1 H), 4.36 (m, 1 H), 7–7.6 (m, 10 H).

3-Ethyl-4,4-diphenylthiazolidine (22). *N*-Oxide **1a** (0.089 g, 1 mmol) and thiobenzophenone (**14**) (0.217 g, 1.1 mmol) were treated with LDA at 0 °C for 3 h. A crude mixture (0.290 g) was obtained after workup. Purification on preparative TLC (CH_2Cl_2) yielded **22** (0.253 g, 0.94 mmol, 94%): MS *m/e* 269, 222, 221, 143, 71; ^{1}H NMR (60 MHz) δ 1.1 (t, 3 H), 2.5 (m, 2 H), 3.6 (s, 2 H), 4.15 (s, 2 H), 7–7.8 (m, 10 H). Picrate: mp 157 °C (EtOH). Anal. Calcd for $C_{23}H_{22}N_4O_7S$: C, 55.42; H, 4.41; N, 11.24; S, 6.42. Found: C, 55.35; H, 4.40; N, 11.54; S, 6.36.

1-Ethyl-3,4-diphenylimidazolidine (23a), 1,2-Dimethyl-3,4-diphenylimidazolidine (23b), and 1,5-Dimethyl-3,4-diphenylimidazolidine (23c). *N*-Oxide **1a** (0.214 g, 2.4 mmol) and benzalaniline (**15**) (0.477 g, 2.6 mmol) were treated with LDA at 0 °C for 3 h. A crude mixture (0.58 g) was obtained after workup. VPC analysis showed that **23a–c** were formed respectively in 6.4:1:0.2 ratio (0.367 g, 1.5 mmol, 62%). Column chromatography allowed their separation. **23a**: MS *m/e* 252, 251, 195, 194, 77, 71; ^{1}H NMR (200 MHz) δ 1.13 (t, 3 H, 2.6 (dd, 1 H), 3.1 (dd, 1 H), 4.08 (d, 1 H, J_{gem} = 4 Hz), 4.53 (d, 1 H), 4.73 (dd, 1 H), 6.53 (d, 2 H), 6.6–7.8 (m, 8 H). Anal. Calcd for $C_{17}H_{20}N_2$: C, 80.95; H, 7.93; N, 11.11. Found: C, 81.20; H, 7.86; N, 10.85. **23b**: ^{1}H NMR (200 MHz) δ 1.56 (d, 3 H, *J* = 6 Hz), 2.56 (s, 3 H), 4.19 (q, 1 H, *J* = 6 Hz).

The same reaction performed at −78 °C was incomplete after 3 h (50% recovered starting product (**15**). TLC purification decomposed the expected products **23a–c**, which were formed in 5.6:1:1.6 ratio.

1-Ethyl-2β-methyl-3β,4β-diphenylpyrrolidine (24a) and 1-Ethyl-2α-methyl-3β,4β-diphenylpyrrolidine (24b). *N*-Oxide **1b** (0.309 g, 3 mmol) and *cis*-stilbene (**10**) (0.66 mL, 3.3 mmol) were treated with LDA at 0 °C for 3 h. A crude mixture (0.75 g) was obtained after workup. VPC analysis showed that **24a** and **24b** were formed in a 0.1 ratio. Column chromatography afforded **24b** (0.32 g, 1.22 mmol, 41%): MS *m/e* 265, 250, 182, 85; ^{1}H NMR (400 MHz) δ 1.17 (d, 3 H, *J* = 6 Hz), 1.26 (t, 3 H, *J* = 7.5 Hz), 2.40 (m, 1 H, J_{gem} = 12 Hz), 2.80 (dd, 1 H), 2.90 (m, 1 H), 3.1 (m, 1 H), 3.32 (m, 1 H), 3.65 (m, 1 H) 3.81 (dd, 1 H), 6.74–7.32 (m, 10 H); **24a** was characterized by a doublet at 0.93 ppm. Anal. Calcd for $C_{19}H_{13}N$: C, 60.72; H, 5.30; N, 11.33. Found: C, 60.60; H, 5.20; N, 11.38.

1-Ethyl-2β-methyl-3β,4α-diphenylpyrrolidine (25a) and 1-Ethyl-2α-methyl-3β,4α-diphenylpyrrolidine (25b). *N*-Oxide **1b** (0.103 g, 1 mmol) and *trans*-stilbene (**11**) (0.198 g, 1.1 mmol) were treated with LDA at 0 °C for 3 h. A crude mixture (0.444 g) was obtained after workup. VPC analysis showed the presence of **25a** and **25b** in a 0.5 ratio. Column chromatography yielded **25a** + **25b** (0.213 g, 0.8 mmol, 80%). Preparative TLC afforded their separation. **25a**: MS *m/e* 265, 250, 178, 91, 85; ^{1}H NMR (200 MHz) δ 0.70 (d, 3 H), 1.26 (t, 3 H), 2.35 (q, 1 H), 2.60 (m, 1 H), 2.90 (m, 1 H), 3.15 (q, 1 H), 3.6 (m, 3 H), 7.1–7.4 (m, 10 H). **25b**: HRMS calcd for $C_{19}H_{23}N$ 265.1789, found 265.1795; ^{1}H NMR

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(200 MHz) δ 1.1 (d, 3 H), 1.2 (t, 3 H), 2.35 (q, 1 H), 2.6 (m, 1 H), 3 (m, 3 H), 3.3 (dd, 1 H), 3.5 (dt, 1 H), 7–7.6 (m, 10 H).

1-Ethyl-3,4-diphenyl-2-methyl-2,5-dihydropyrrole (26a). *N*-Oxide **1b** (0.268 g, 2.6 mmol) and diphenylacetylene (**13**) (0.463 g, 2.6 mmol) were treated with LDA at −78 °C for 4 h. A crude mixture (0.593 g) was obtained after workup. Preparative TLC (CH_2Cl_2–MeOH (90/10)) afforded **13** (0.27 g, 1.56 mmol, 60%) and **26a** (0.272 g, 1.03 mmol, 39%): MS *m/e* 263, 262, 249, 186, 167, 124; ^1H NMR (200 MHz) δ 1.12 (d, 3 H, J = 7 Hz), 1.18 (t, 3 H), 2.6 (dq, 1 H, J_{gem} = 13 Hz), 3.0 (dq, 1 H), 3.60 (dd, 1 H, J_{gem} = 14 Hz, J = 4 Hz), 4.02 (m, 1 H), 4.39 (dd, 1 H), J_{gem} = 14 Hz, J = 4 Hz), 7.16 (m, 10 H). Picrate: mp 99–100 °C (EtOH). Anal. Calcd for $C_{25}H_{24}H_4O_7$: C, 60.98; H, 4.88. Found: C, 60.71; H, 4.83.

1-Ethyl-3,4-diphenyl-2-methylpyrrole (26b). Pyrroline **26a** (0.030 g, 0.11 mmol) was treated with 5% Pd/C at room temperature in methanol for 50 h to yield **26b** quantitatively: MS *m/e* 261; ^1H NMR (200 MHz) δ 1.39 (t, 3 H), 2.18 (s, 3 H), 3.86 (dq, 2 H), 6.73 (s, 1 H), 6.86 (m, 10 H).

3-Ethyl-5,5-diphenyl-4-methylthiazolidine (27a) and 3-Ethyl-5,5-diphenyl-2-methylthiazolidine (27b). *N*-Oxide **1b** (0.55 g, 0.5 mmol) and thiobenzophenone (**14**) (0.099 g, 0.5 mmol) were treated with LDA at 0 °C for 2 h. A crude mixture (0.159 g) was obtained after workup. VPC analysis revealed the presence of **27a** and **27b** in a 1.6 ratio. Preparative TLC (hexane–CH_2Cl_2 (80/20)) afforded the two isomers. **27a** (0.029 g, 0.1 mmol, 22%): MS *m/e* 283, 210, 181, 164, 85; ^1H NMR (200 MHz) δ 0.90 (d, 3 H, J = 7 Hz), 1.20 (t, 3 H), 2,56 (m, 1 H), 2.89 (m, 1 H), 3.86 (d, + q, 2 H, J = 7 Hz), 4.29 (d, 1 H, J = 7 Hz), 7.78 (m, 10 H). **27b** (0.011 g, 0.038 mmol, 8%): MS *m/e* 283, 268, 211, 165, 85; ^1H NMR (200 MHz) δ 1.1 (t, 3 H), 1.50 (d, 3 H, J = 6 Hz), 2.36 (m, 1 H), 2.73 (m, 1 H), 3.36 (d, 1 H, J = 11 Hz), 4.09 (d, 1 H, J = 11 Hz), 4.32 (q, 1 H, J = 6 Hz), 7–7.8 (m, 10 H).

1-Ethyl-3,4-diphenyl-5-methylimidazolidine (28a) and 1-Ethyl-3,4-diphenyl-2-methylimidazolidine (28b). *N*-Oxide **1b** (0.32 g, 3.10 mmol) and benzalaniline (**15**) (0.641 g, 3.41 mmol) were treated with LDA at 0 °C for 3 h. A crude mixture (0.880) was obtained after workup. **28a,b** were formed in 65% yield as determined by NMR. VPC analysis showed the presence of **28a** and **28b** in a 0.1 ratio. Preparative TLC (CH_2Cl_2) afforded **28b** (0.350 g, 1.50 mmol, 42%) and **28a**. **28b**: MS *m/e* 266, 251, 195, 194, 181, 85; HRMS calcd for $C_{18}H_{22}N_2$: 266.1789, found 266.1778; ^1H NMR (400 MHz) δ 1.08 (t, 3 H), 1.54 (d, 3 H), 2.04 (m, 1 H), 2.73 (m, 1 H), 3.15 (m, 1 H), 3.19 (m, 1 H), 4.45 (q, 1 H), 4.71 (dd, 1 H), 6.3–7.5 (m, 10 H). **28a**: ^1H NMR (400 MHz) δ 1.18 (t, 3 H), 1.22 (d, 3 H), 2.28 (q, 1 H), 2.59 (m, 1 H), 2.93 (m, 1 H), 6.3–7.5 (m, 10 H).

1-Ethyl-2-methyl-3-phenyl-4-(trimethylsilyl)-2,5-dihydropyrrole (29a) and 1-Ethyl-2-methyl-4-phenyl-3-(trimethylsilyl)-2,5-dihydropyrrole (29b). *N*-Oxide **1b** (0.164 g, 1.6 mmol) and protected phenylacetylene **16** (0.278 g, 1.6 mmol) were treated with LDA at 0 °C for 4 h. A crude mixture (0.461 g) was obtained after workup. VPC analysis revealed the presence of **29a** and **29b** in a 0.25 ratio. Preparative TLC (CH_2Cl_2–MeOH (97/3)) afforded **29a** (0.027 g, 0.1 mmol, 6.5%) and **29b** (0.280 g, 1.08 mmol, 68%). **29a**: MS *m/e* 259, 257, 244, 186, 73; ^1H NMR (200 MHz) δ 0 (s, 9 H), 1.22 (t,3 H), 1.32 (d, 3 H), 2.64 (dq, 1 H), 2.94 (dq, 1 H), 3.6–4.4 (m, 2 H), 7–8 (m, 10 H). **29b**: HRMS calcd for $C_{16}H_{25}NSi$ 259.1770, found 259.1769; ^1H NMR (200 MHz) δ 0 (s, 9 H), 1.20 (d, 3 H), 1.29 (dd, 3 H, J = 7.5 Hz) 2.66 (dq, 1 H, J = 12 Hz), 3.07 (dq, 1 H), 3.47 (dd, 1 H, J_{gem} = 13 Hz, J = 5 Hz), 3.93 (dq, 1 H, J = 5 Hz), 4.2 (dd, 1 H, J = 4 Hz), 7 (m, 5 H).

1-Ethyl-2-methyl-3-phenylpyrrolidine (30a and 30b) and 1-Ethyl-2-methyl-4-phenylpyrrolidine (30c and 30d). *N*-Oxide **1b** (0.309 g, 3 mmol) and styrene (0.260 g, 2.5 mmol) were treated with LDA at 0 °C for 3 h. A crude mixture (0.387 g) was obtained after workup. VPC analysis showed the presence of **30c**, **30a** + **30b**, and **30b** in a 1:4.2:1 ratio; **30a**/(**30b** + **30c** + **30d**) was shown by NMR analysis to be equal to 1.2. Preparative TLC (CH_2Cl_2–MeOH (97/3)) afforded 0.323 g (1.85 mmol, 74%) of various fractions in which **30a–c** were obtained in pure form. The stereochemistry was not attributed to **30c,d**. MS *m/e* 189, 175, 85. Picrate: Anal. Calcd. for $C_{19}H_{22}N_4O_7$: C, 54.54; H, 5.26; N, 13.39. Found: C, 54.26; H, 5.31; N, 13.20. **30a**: ^1H NMR (200 MHz) δ 0.75 (d, 3 H, J = 6.5 Hz), 1.27 (t, 3 H, J = 7.5 Hz), 2.23 (m, 2 H), 2.53 (m, 1 H), 2.72 (m, 1 H, J_{Gem} = 7 Hz), 3.0 (m, 1 H), 3.15 (m, 1 H), 3.33 (m, 1 H), 3.57 (dt, 1 H, J = 8 Hz), 7.36 (m, 5 H). **30b**: ^1H NMR (200 MHz) δ 1.12 (t, 3 H, J = 8 Hz), 1.17 (d, 3 H, J = 6.6 Hz), 1.37–1.73 (m, 1 H, J_{gem} = 8 Hz), 2.04–2.24 (m, 1 H, J_{gem} = 12 Hz), 2.24–2.46 (m, 1 H), 2.46–2.59 (m, 1 H, J = 6.6 Hz), 2.59–2.83 (dd, 1 H, J = 11.5 Hz), 2.83–3.09 (m, 1 H), 3.09–3.56 (m, 2 H), 7.16–8.0 (m, 5 H). **30c**: ^1H NMR (200 MHz) δ 1.18 (t, 3 H), 1.25 (d, 3 H), 1.9–2.2 (m, 2 H), 2.2–2.4 (m, 2 H), 2.5–2.9 (m, 1 H), 2.9–3.2 (dt, 1 H), 3.4–3.5 (m, 1 H), 3.4–3.6 (m, 1 H).

1,2-Diphenyl-1,5,6,7,8,8a-hexahydroindolizine (31). *N*-Oxide **1c** (0.23 g, 2 mmol) and diphenylacetylene (**13**) (0.36 g, 2 mmol) were treated with LDA at 0 °C for 4 h. A crude mixture (0.627 g) was obtained after workup. Preparative TLC (ether) afforded **31** (0.362 g, 1.32 mmol, 66%): MS *m/e* 275, 233, 199; ^1H NMR (200 MHz) δ 1–2 (m, 6 H), 2.5–2.7 (m, 1 H, J = 12 Hz), 3–3.3 (m, 1 H, J = 12 Hz), 3.3–3.6 (m, 1 H), 3.63 (dd, 1 H, J_{gem} = 12 Hz, J = 5 Hz), 4.20 (dd, 1 H, J_{gem} = 12 Hz, J = 3 Hz), 6.7–7.8 (m, 10 H); mp 90 °C (MeOH). Anal. Calcd for $C_{20}H_{21}N$: C, 87.27; H, 7.64. Found: C, 87.16; H, 7.68.

1-Aza-1,2-diphenyloctahydroindolizine (32). *N*-Oxide **1c** (0.28 g, 2.43 mmol) and benzalaniline (**15**) (0.484 g, 2.67 mmol) were treated with LDA at −78 °C for 3 h. A crude mixture (0.800 g) was obtained after workup. Preparative TLC (CH_2Cl_2–MeOH (99/1) afforded **32** (0.480 g, 1.72 mmol, 71%): MS *m/e* 278, 277, 249, 222, 201, 97; ^1H NMR (200 MHz) δ 1.58 (m, 4 H), 1.9 (d, 1 H, J = 10 Hz), 2.36 (dt, 1 H), 2.46 (d, 1 H), 2.95 (dd, 1 H, J_{gem} = 7 Hz), 3 (m, 2 H), 3.58 (d, 1 H), 4.5 (d, 2 H), 6.6–7.7 (m, 10 H); mp 115 °C (CH_2Cl_2). Anal. Calcd for $C_{19}H_{22}N_2$: C, 82.01; H, 7.91; N, 10.07. Found: C, 81.77; H, 7.93; N, 9.80.

Generation of Diatomic Sulfur from Organometallic Precursors[1]

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Diatomic sulfur, generated from different titanium and zirconium pentasulfides (**5a,b**), has been successfully trapped by dienes.

The first chemical generation of diatomic sulfur ($^1S_2$) was achieved in 1984 by the decomposition of a germanium trisulfide species (**1**) with triphenylphosphine dibromide (**2**).[2a] Evidence for the existence of S_2 was accomplished

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