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Improved Synthesis of Pyrroles and Indoles *via* Lewis Acid-Catalyzed Mukaiyama–Michael-Type Addition/Heterocyclization of Enolsilyl Derivatives on 1,2-Diaza-1,3-Butadienes. Role of the Catalyst in the Reaction Mechanism

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Abstract: The Mukaiyama–Michael-type addition of various silyl ketene acetals or silyl enol ethers on some 1,2-diaza-1,3-butadienes proceeds at room temperature in the presence of catalytic amounts of Lewis acid affording by heterocyclization 1-aminopyrrol-2-ones and 1-aminopyrroles, respectively. 1-Aminoindoles have been also obtained by the same addition of 2-(trimethylsilyloxy)-1,3-cyclohexadiene on some 1,2-diaza-1,3-butadienes and subsequent aromatization. Mechanistic investigations indicate the coordination by Lewis acid of the enolsilyl derivative and its 1,4-addition on the azo-ene system of 1,2-diaza-1,3-butadienes. The migration of the silyl group from a hydrazonic to an amidic nitrogen, its acidic cleavage and the final internal heterocyclization give the final products. Based on NMR studies and *ab initio* calculations, a plausible explanation for the migration of the silyl protecting group is presented.

Keywords: 1,2-diaza-1,3-butadienes; Lewis acids; Mukaiyama–Michael reaction; silyl enol ethers; silyl group rearrangement; silyl ketene acetals

Introduction

Michael addition to α,β-unsaturated systems is one of the most important bond-forming processes in organic chemistry and offers an extremely powerful tool for the synthesis of highly functionalized organic molecules.[1] Therefore, extensive studies have been done on the development of catalytic asymmetric Michael procedures for various useful donor-acceptor combinations.[2,3] The Lewis acid-catalyzed analogue of the Michael addition, introduced by Mukaiyama and coworkers,[4] occurs between silyl enol ethers and α,β-unsaturated carbonyl substrates in the presence of various catalysts.[5]

In connection with an ongoing interest in developing new synthetic strategies for the construction of heterocyclic rings[6,7] from 1,2-diaza-1,3-butadienes, we report here the results of the reactions between the latter compounds and some silyl ketene acetals or silyl enol ethers in the presence of a Lewis acid. We have developed a protocol for building up both 1-aminopyrrol-2-one and 1-aminopyrrole rings involving a combined Mukaiyama–Michael-type addition/heterocyclization reaction. Furthermore, we here describe the synthesis of some 1-aminoindole derivatives by Mukaiyama–Michael-type addition of 2-(trimethylsilyloxy)-1,3-cyclohexadiene on 1,2-diaza-1,3-butadienes followed by an aromatization process.

The pyrrole-type ring widely occurs in organic (i.e., pyrroles, indoles, carbazoles, and their hydro-derivatives), polymeric (i.e., polypyrroles), biological (i.e., porphyrins and hemes, phthalocyanines, chlorophylls and bacteriochlorophylls, bile pigments and phycobilins, alkaloids, amino acids), pharmaceutical (i.e., vitamin B_{12}, pyrrolnitrin, fenpiclonil, pyrvinium, stallimycin, tolmetin, zomepirac, clemizole, dextromoramide, triprolidine, piracetam, anirolac, prostaglandin $PGF_{2\alpha}$, vinblastine, vincristine, vincamine, reserpine) and phytopharmaceutical (i.e., perfluoroalkylpyrroles) chemistry.[8] Recently, 1-aminopyrroles were used as precursors in the synthesis of biologically active com-

pounds such as analgesics[9] and NMDA receptor antagonists.[10]

Two possible reaction pathways to form the Mukaiyama–Michael adduct between an enolsilyl derivative and a 1,2-diaza-1,3-butadiene could be hypothesized: a stepwise mechanism involving firstly a concerted [4+2] cycloaddition (hetero-Diels–Alder reaction), followed by a ring opening pathway or a "classical" Mukaiyama–Michael-type addition (Figure 1).

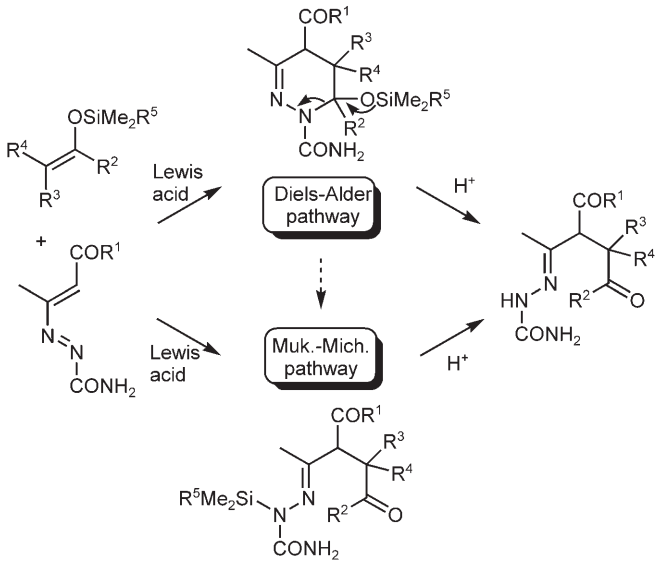


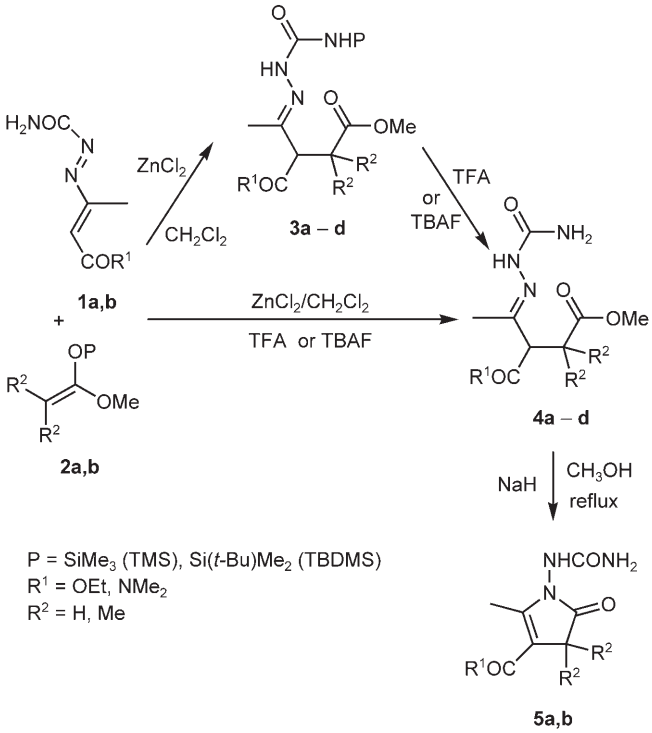
Figure 1. Possible reaction pathways for the addition of enolsilyl derivatives on 1,2-diaza-1,3-butadienes.

Our findings suggest that the mechanism of the Mukaiyama–Michael-like additions here reported proceeds *via* the coordination of the enolsilyl derivative by the Lewis acid and its 1,4-conjugate addition on the azo-ene system of the 1,2-diaza-1,3-butadiene. The subsequent migration of the silyl group from a hydrazonic to an amidic nitrogen, its acidic cleavage and the final internal heterocyclization afford the afore-mentioned products.

Results and Discussion

Addition of Silyl Ketene Acetals 2a,b on 1,2-Diaza-1,3-butadienes 1a,b

Initially, we screened a number of Lewis acids in order to find the most suitable catalyst for the addition of enolsilyl derivatives on 1,2-diaza-1,3-butadienes.[11] We chose to use the addition of 1-methoxy-2-methyl-1-(trimethylsiloxy)propene **2a** on 1,2-diaza-1,3-butadiene **1a**, that by an opportune work-up provided the adduct **4a** to test the catalytic activity of $LiClO_4$, $AlCl_3$, $TiCl_4$, $Sc(TfO)_3$, $Cu(TfO)_2$, $ZnCl_2$, $Y(TfO)_3$, $InCl_3$, $InBr_3$, $In(TfO)_3$, $SnCl_4$, SmI_2, $Sm(TfO)_3$, $Yb(TfO)_3$, $Bi(TfO)_3$ (Scheme 1). Among the fifteen Lewis acids tested, eleven exhibited remarkable catalytic activity (Table 1). Only four of them (i.e., $AlCl_3$, $TiCl_4$, $SnCl_4$, SmI_2) did not affect the course of the reaction, or even provided only chlorohydrazonic adducts as well as degradation products.



Scheme 1. Mukaiyama-Michael-type addition/heterocyclization reaction of silyl ketene acetals **2a,b** on 1,2-diaza-1,3-butadienes **1a,b**.

Table 1. Screening activity of various Lewis acids for the addition of 1-methoxy-2-methyl-1-(trimethylsiloxy)propene **2a** on 1,2-diaza-1,3-butadiene **1a** giving the adduct **4a**.

Entry[a]	Catalyst	Reaction time	Product **4a** Yield [%][b]
1	$LiClO_4$	1 h	96
2	$Sc(TfO)_3$	2 h	97
3	$Cu(TfO)_2$	15 min	94
4	$ZnCl_2$	5 h	97
5	$Y(TfO)_3$	24 h	91
6	$InCl_3$	2 h	91
7	$InBr_3$	10 min	97
8	$In(TfO)_3$	8 h	91
9	$Sm(TfO)_3$	23 h	87
10	$Yb(TfO)_3$	4 h	95
11	$Bi(TfO)_3$	30 min	97

[a] All of the reactions were carried out at room temperature by using 1,2-diaza-1,3-butadiene **1a** (1 mmol), silyl ketene acetal **2a** (1.2 mmol), and catalyst (0.2 mmol). The crude reaction mixtures were treated with TFA to afford the adduct **4a**.

[b] Isolated yield after chromatographic purification.

As practically all of the eleven catalysts reported in Table 1 furnished **4a** with yields from high to excellent (from 87 to 97%), only requiring variable reaction times (from a few minutes to several hours), our choice of $ZnCl_2$ was based on the following considerations: 1) it catalyzes the reaction with excellent yield (97%); 2) the time of reaction appears in line with the necessity of carrying out a series of experiments; 3) $ZnCl_2$ shows a high stability and moisture resistance together with a low cost and a high ecocompatibility with respect to all of the other catalysts tested.

Thus, we extended our investigations to the additions of silyl ketene acetals **2a,b** on 1,2-diaza-1,3-butadienes **1a,b** in dichloromethane with a catalytic amount (20 mol%) of $ZnCl_2$ to obtain the adducts **4a–d** (Scheme 1, Table 2).

In order to directly obtain the desilylated hydrazonic 1,4-adducts **4a–d** in good yields, the respective crude reaction mixtures from additions of silyl ketene acetals **2a,b** on 1,2-diaza-1,3-butadienes **1a,b** in dichloromethane with a catalytic amount (20 mol%) of $ZnCl_2$ were directly treated with trifluoroacetic acid (TFA) or tetrabutylamonium fluoride (TBAF) after the disappearance of 1,2-diaza-1,3-butadienes **1a,b**. The subsequent treatment of **4a,b** with sodium hydride in methanol under reflux gives rise to pyrrol-2-ones **5a,b** in good yields by ring closure ascribable to the internal nucleophilic attack of the hydrazonic nitrogen at the ester group with the elimination of a molecule of methanol (Scheme 1, Table 2).

Regiochemistry, Stereochemistry and Mechanism

Although as a mixture with the corresponding products **4a–d**, it was also possible to isolate the silyl adducts **3a,d** in good yields by flash chromatography of the crude reaction mixtures immediately after the disappearance of the starting 1,2-diaza-1,3-butadienes **1a,b** (3–5 h; the progress of the reaction was monitored by looking at the change of the reaction mixtures from the initial red color of 1,2-diaza-1,3-butadiene to the final pale yellow one and by TLC). The exact structure of these adducts was determined by NOE experiments which proved the relationship shown in Figure 2 for **3c**, supporting the formation of only the *E*-semicarbazone (probably the more stable, see below) by means of a completely stereospecific reaction.

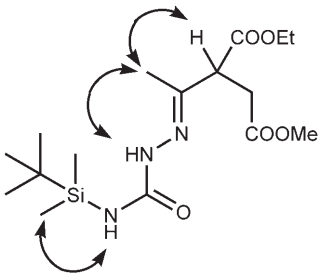


Figure 2. Observed NOE for compound **3c**.

In our opinion, these products could arise from silyl group migration to the terminal amidic nitrogen from the hydrazonic one initially formed by 1,4-addition of the enolsilyl derivatives **2a,b** on the azo-ene system of the 1,2-diaza-1,3-butadienes **1a,b**.

The mechanism generally accepted for the Lewis acid-catalyzed Mukaiyama–Michael addition of enolsilyl derivatives on Michael acceptors involves the coordination of the Michael acceptor with the Lewis acid followed by the 1,4-addition of the enol form.[12] In an attempt to find experimental proof in support

Table 2. Results of the $ZnCl_2$-catalyzed Mukaiyama–Michael-type addition/heterocyclization reaction of silyl ketene acetals **2a,b** on 1,2-diaza-1,3-butadienes **1a,b**.

Entry	**1**	R^1	**2**	P	R^2	Product **3** Yield [%][a–c]	Product **4** Yield [%]	Product **5** Yield [%][f]
1	**1a**	OEt	**2a**	$SiMe_3$	Me	**3a** (56)	**4a** (97)[d]	**5a** (75)
2	**1b**	NMe_2	**2a**	$SiMe_3$	Me	**3b** (51)	**4b** (93)[d]	**5b** (80)
3	**1a**	OEt	**2b**	Si(*t*-Bu)Me_2	H	**3c** (44)	**4c** (78)[e]	
4	**1b**	NMe_2	**2b**	Si(*t*-Bu)Me_2	H	**3d** (54)	**4d** (81)[e]	

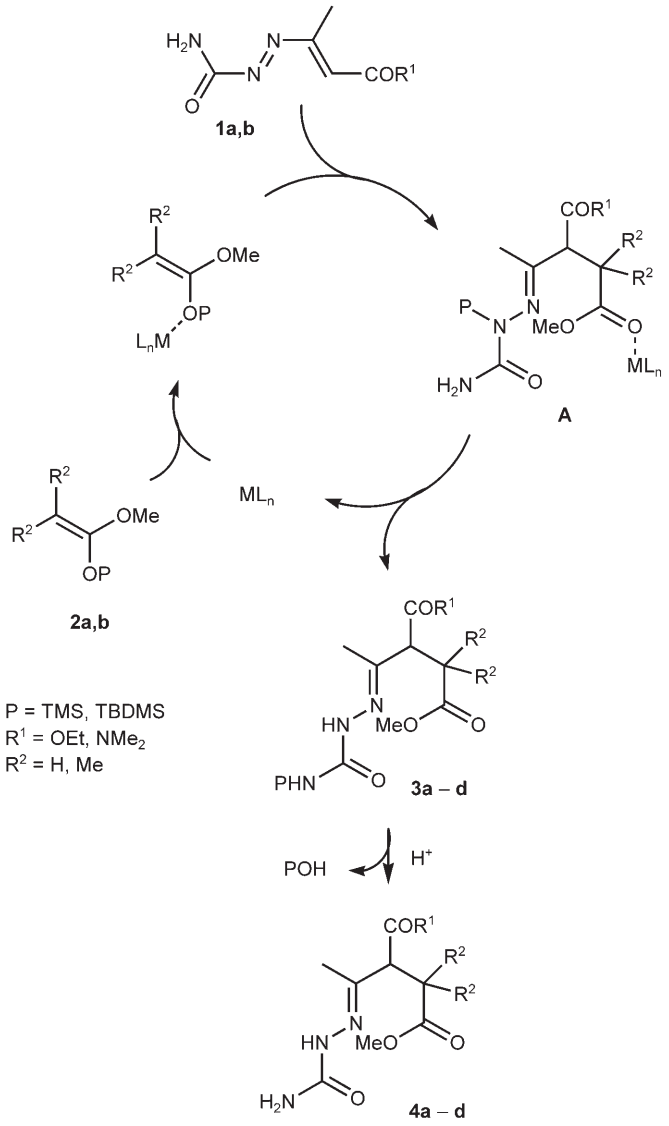
[a] All of the reactions were carried out at room temperature for 3–5 h by using 1,2-diaza-1,3-butadienes **1a,b** (1 mmol), silyl ketene acetals **2a,b** (1.2 mmol), and $ZnCl_2$ (0.2 mmol).
[b] Isolated yield by chromatographic purification carried out immediately after the disappearance of 1,2-diaza-1,3-butadiene.
[c] The remaining products are **4a-d**, respectively.
[d] After the disappearance of 1,2-diaza-1,3-butadiene, the crude reaction mixtures were treated with TFA to afford the products **4a,b**.
[e] After the disappearance of 1,2-diaza-1,3-butadiene, the crude reaction mixtures were treated with TBAF to afford the products **4c,d**.
[f] All of the reactions were carried out by treatment of **4** (1.0 mmol) in methanol with the stoichiometric amount of NaH (1.0 mmol) under reflux for 12 h.

of the proposed behavior of these reactions, we monitored the progress of the addition of diaza-1,3-butadiene **1a** on 1-methoxy-2-methyl-1-(trimethylsiloxy)-propene **2a** by ^{1}H NMR spectroscopy directly in a NMR tube using $CDCl_3$ as a solvent.

Firstly, no appreciable shift variation was observed either in ^{1}H or ^{13}C NMR spectra for the signals of 1,2-diaza-1,3-butadiene **1a** when $ZnCl_2$ was added to this compound under the same experimental conditions showing that the Lewis acid does not interact with this compound. When silyl ketene acetal **2a** was added to this mixture, we detected, after a few minutes, the appearance of a set of signals ascribable to the products **3a** and **4a** and at the same time the disappearance of the signals of the starting materials 1,2-diaza-1,3-butadiene **1a** and silyl ketene acetal **2a**. In addition, a singlet at 1.87 ppm (ascribable to CH_3), a singlet at 3.78 ppm (ascribable to CH) and a broad singlet at 4.88 ppm (ascribable to NH_2) rapidly appeared and gradually decreased. These signals were assigned to the short-lived intermediate **A** (Scheme 2). After about 4 h, all of the signals attributable to starting materials and transient species disappeared, and only the peaks pertinent to the products **3a** [$\delta = 1.85$ (CH_3), 3.60 (CH), 5.88 (NHSi) and 9.53 (NH)] and **4a** [$\delta = 1.85$ (CH_3), 3.60 (CH), 5.25 and 6.22 (NH_2) and 9.20 (NH)] could be observed. Quenching with TFA caused a selective disappearance of the signals corresponding to Michael-type 1,4-adduct silyl derivative **3a** and only the resonances of desilylated product **4a** were detected.

Based on these combined findings, we propose the mechanism reported in Scheme 2. The enolsilyl derivative **2** coordinated with the Lewis acid (ML_n) adds on the 1,2-diaza-1,3-butadienes **1** to give the corresponding intermediates **A**. The following regeneration of the Lewis acid catalyst and the migration of the silyl group from the hydrazonic to the amidic nitrogen atom allows the shut-down of both the catalytic cycle and the formation of the final products. In fact, unlike other Michael acceptors, 1,2-diaza-1,3-butadienes fortunately possess a hydrazone nitrogen as an efficient linker. In this way, the azoalkene substrate acted also as a silyl trapping agent. The migration of the silyl group to the terminal nitrogen and its final loss represent the driving force of the reaction.

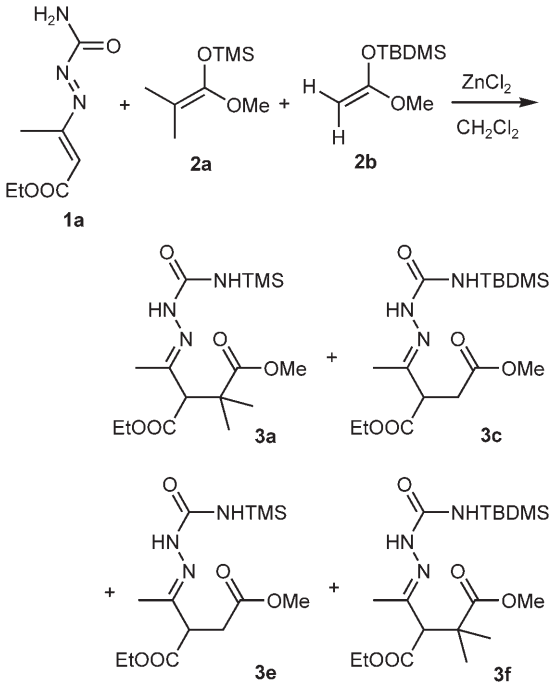
To gain further information about the mechanism of the transfer of the silyl group from the enolsilyl derivative to the amidic nitrogen of the Michael-type 1,4-adduct, we have carried out a cross-over experiment which resembles that proposed by Mikami and Matsukawa[13] in order to ascertain the pathway of the aldol-like reactions. When 1,2-diaza-1,3-butadiene **1a** reacted with a mixture of **2a** and **2b** in dichloromethane with a catalytic amount (20 mol%) of $ZnCl_2$, the formation of the expected **3a** and **3c** together with that of **3e** and **3f** was evidenced. Interestingly, a mixture of equal quantities of the four silylated Michael-type 1,4-adducts **3a,c,e,f** was obtained in high yields (88%) (Scheme 3). This result clearly demonstrates that the pathway of the Mukaiyama–Michael-type reaction is globally an intermolecular process.



Scheme 2. Proposed mechanism for the Lewis acid-catalyzed Mukaiyama–Michael-type addition of enolsilyl derivatives **2a,b** on 1,2-diaza-1,3-butadienes **1a,b**.

These results indicate that the scrambling took place during the Mukaiyama–Michael-type reaction, consistent with the open-chain mechanism, with the particularity, in our case, that the silicon atom is trapped by the Michael-type adduct silyl derivatives **3a,c,e,f**.

Based on the ^{1}H NMR study of reaction mixtures, we hypothesized that the addition of silyl ketene acetals **2a,b** on 1,2-diaza-1,3-butadienes **1a,b**, in the presence of $ZnCl_2$, occurs *via* some transient products. The first appearance and then the fast disappearance



Scheme 3. Crossover experiment for the Mukaiyama–Michael-type addition of silyl ketene acetals **2a** and **2b** on 1,2-diaza-1,3-butadiene **1a**.

of the signals at 1.87, 3.78 and 4.88 ppm seems to be clear evidence in favor of the formation of short-lived intermediates **A** (i.e., the expected 1,4-addition product of **2a,b** on **1a,b**; see Scheme 2) able to give firstly **3a–d** and then **4a–d** in high yields.

Now, we will make some comments on the hypothesized rearrangement of **A** intermediates into **3a–d**, examining the possible reasons for the transformation, advancing some hypotheses on its occurrence, and then possibly offering a first proposal on its mechanism.

It is well known that a "spontaneous" rearrangement occurring during the course of a reaction and/or during its work-up "must" be thermodynamically driven. That is, the "less stable" firstly formed product "can" ("can" means that this fact occurs only if the activation energy of the process is quite low considering the reaction experimental conditions) give the "more stable" one.

We performed some calculations on simplified model systems to give a qualitative confirmation to our hypotheses. All calculations were performed at the DFT[14] level with the Gaussian03 series of programs[15] using the B3LYP[16] functional; in all calculations the solvent (CH_2Cl_2) was simulated using the SCRF/CPCM[17] method. A locally dense basis set (LDBS)[18] approach has been adopted. Preliminary calculations at the STO-3G level allowed a fast and rough exploration of PES to individualize the most stable conformers; the so-obtained candidate geometries have been optimized at the DZVP[19] level, thus obtaining results reported in the Supporting Information.

NOE experiments indicated an *E*-relationship for **3c**; to gain support for this result we calculated the stability of **A** and of **3** using the simplified models reported in Figure 3 and indicated as *E*-**X** and *E*-**Y**, respectively.

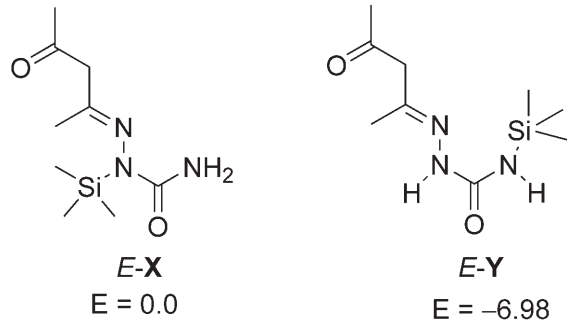


Figure 3. Simplified models for *E*-isomers of **A** and **3**: *E*-**X** and *E*-**Y** [calculated differences (kcal mol^{-1}) in energy contents are reported].

In line with previsions, *E*-**Y** resulted to be much more stable than *E*-**X** ($\Delta E°$ *ca.* 7 kcal mol^{-1}). This result supports the reasonable hypothesis that the spontaneous rearrangement is thermodynamically driven. It is also interesting to point out that if an equilibrium between *E*-**X** and *E*-**Y** were present, the stability gap would ensure an almost complete shift towards *E*-**Y**, since the equilibrium constant, K_{eq}, is as large as 10^5 at room temperature.

Having ascertained the significant difference in the energy content between *E*-**X** and *E*-**Y**, now by a deeper analysis of models it should be possible to understand the reason for this fact.

We ascribe the lesser stability of *E*-**X** in respect to *E*-**Y** to an higher overcrowding in the first regioisomer, in fact the two structures do extend, respectively, in 8.44 and 12.62 Å (Figure 4). This fact causes in *E*-**X**

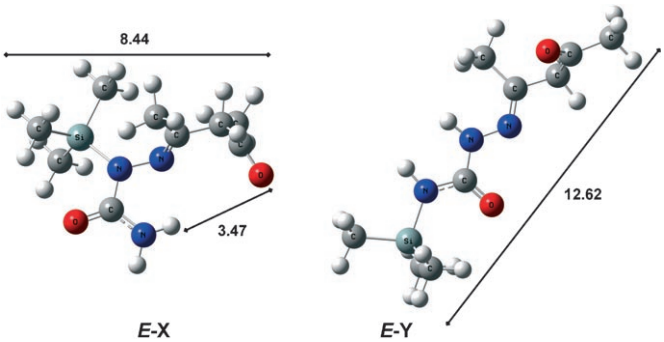


Figure 4. Three-dimensional representations for *E*-**X**, and *E*-**Y**. Reported distances are in Å.

strong steric interactions between one of the methyls of the trimethylsilyl group and that at the old C-3 of the 1,2-diaza-1,3-butadiene, that cannot be released by rotation along the single N–N bond because this would result in a larger overlap between bulkier groups: accordingly we failed in all attempts to find other *minima* when rotating along this bond.

We have also examined the structures and the relative stability of the *Z*-isomers to gain information useful for the understanding of the reasons by which only the formation of the *E*-isomers (*E*-**X** and *E*-**Y**) has been observed. This calculation could be easily carried out with the relevant models of *Z*-**Y** and *Z*-**X**, respectively (Figure 5).

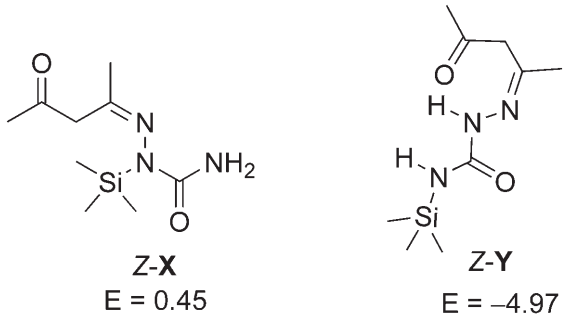


Figure 5. Simplified models for *Z*-isomers of **A** and **3**: *Z*-**X** and *Z*-**Y** [calculated differences (kcal mol^{-1}) in energy contents with respect to *E*-**X** are reported].

The *Z*-isomers are less stable than *E*-isomers by 2 and 0.5 kcal mol^{-1}, respectively, that is, values well in line with the usual observed differences between *E* and *Z* stereoisomers. Of course comments as above made on *E*-**X** and *E*-**Y** can be attached to *Z*-**X** and *Z*-**Y** models. Interestingly an examination of *Z*-**Y** (Figure 6) evidences the presence of a feeble hydrogen bond (2.08 Å) between the carbonyl group and the hydrazonic proton.

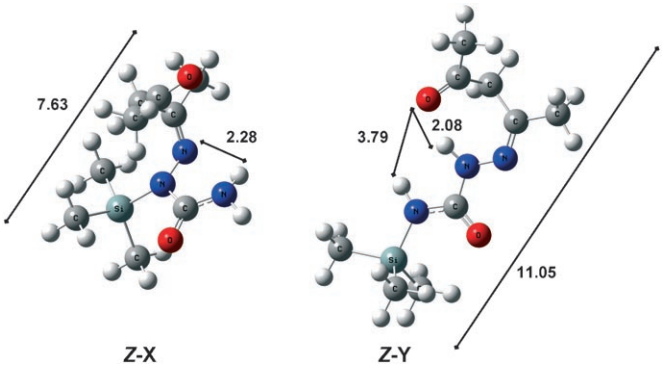
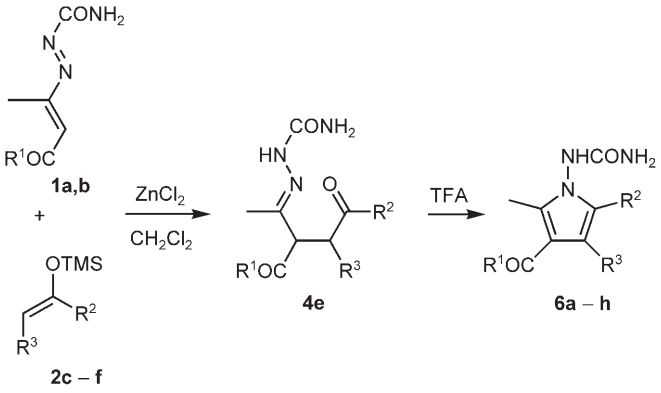


Figure 6. Three-dimensional representations for *Z*-**X**, and *Z*-**Y**. Reported distances are in Å.

Concerning the possible mechanism of the rearrangement, two pathways appear, in principle, to be possible: an intramolecular path, occurring *via* a cyclic four-membered transition state, and an intermolecular one, occurring *via* a presumably more stable cyclic eight-membered transition state. The results of cross-over experiments (see Scheme 3) seem able to support the idea that an intermolecular process occurs. Research in progress is devoted to a deeper understanding of this point.

Addition of Silyl Enol Ethers 2c–f on 1,2-Diaza-1,3-butadienes 1a,b

We have also examined the addition of silyl enol ethers **2c-f** on 1,2-diaza-1,3-butadienes **1a,b** carried out at room temperature in dichloromethane with a catalytic amount (20 mol%) of $ZnCl_2$. After the disappearance of 1,2-diaza-1,3-butadienes **1a,b** (the progress of the reaction was monitored looking at the change of the reaction mixture from the initial red color of 1,2-diaza-1,3-butadiene to the final pale yellow one and by TLC), the crude reaction mixture was quenched with TFA affording in one-pot the 1-aminopyrroles **6a–h** in good yields (Scheme 4, Table 3).



Scheme 4. Mukaiyama–Michael-type addition/heterocyclization reaction of silyl enol ethers **2c–f** on 1,2-diaza-1,3-butadienes **1a,b**.

As supported by the isolation of the intermediate 1,4-adduct **4e** (Figure 3, Table 3), likely these reactions occur by the preliminary formation of the Michael-type adduct with subsequent ring closure due to the intramolecular nucleophilic attack of the hydrazonic nitrogen at the carbonyl group with loss of a water molecule to give the 1-aminopyrrole derivatives according to our previous results.[6]

Table 3. Results of the $ZnCl_2$-catalyzed Mukaiyama–Michael-type addition/heterocyclization reaction of silyl enol ethers **2c–f** on 1,2-diaza-1,3-butadienes **1a,b**.

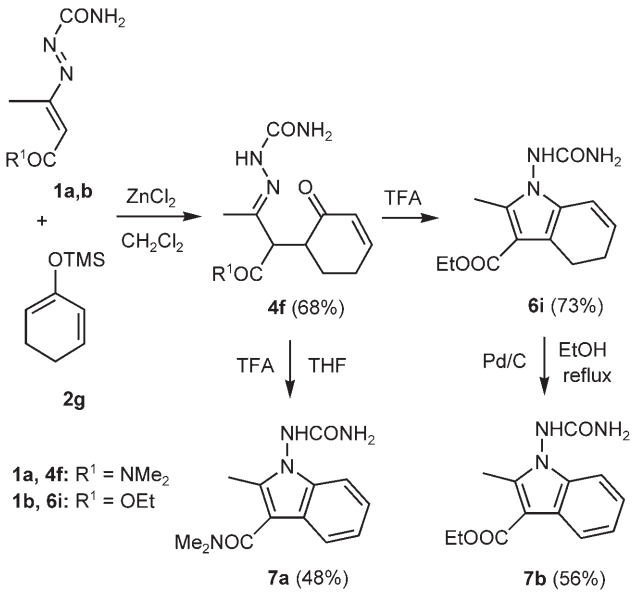
Entry[a]	1	R^1	2	R^2	R^3	Product **4** Yield [%][b]	Product **6** Yield [%][b]
1	**1a**	OEt	**2c**	H	H		**6a** (18)
2	**1b**	NMe_2	**2c**	H	H		**6b** (28)
3	**1a**	OEt	**2d**	Me	H		**6c** (86)
4	**1b**	NMe_2	**2d**	Me	H		**6d** (41)
5	**1a**	OEt	**2e**	Ph	H		**6e** (79)
6	**1b**	NMe_2	**2e**	Ph	H	**4e** (39)	**6f** (50)
7	**1a**	OEt	**2f**	$-(CH_2)_4-$			**6g** (55)
8	**1b**	NMe_2	**2f**	$-(CH_2)_4-$			**6h** (26)

[a] All of the reactions were carried out at room temperature for 20–24 h by using 1,2-diaza-1,3-butadienes **1a,b** (1,0 mmol), silyl enol ethers **2c–f** (1.2 mmol), and $ZnCl_2$ (0.2 mmol). After the disappearance of 1,2-diaza-1,3-butadienes **1a,b**, the crude reaction mixtures were treated with TFA affording the products **4e** and **6a–h**.

[b] Isolated yield after chromatographic purification.

Addition of 2-(Trimethylsilyloxy)-1,3-cyclohexadiene 2g on 1,2-Diaza-1,3-butadienes 1a,b

To enlarge the scope of the examined reactions, we have looked at the possible synthesis of indoles. Thus, we have found an interesting application of these Mukaiyama–Michael reactions obtaining the 1-aminoindole derivatives **7a,b** by addition of 2-(trimethylsilyloxy)-1,3-cyclohexadiene **2g** on 1,2-diaza-1,3-butadienes **1a,b** in dichloromethane with a catalytic amount (20 mol%) of $ZnCl_2$ (Scheme 5). The usual Michael-type 1,4-adduct **4f**, gives both heterocyclization and spontaneous dehydrogenation-aromatization of the cyclohexadienyl ring with TFA in tetrahydrofuran leading directly to the indole **7a**. On the other hand, indole **7b** was obtained by dehydrogenation-aromatization of the cyclohexadienyl ring with Pd/C in EtOH from the relevant 1-aminopyrrole **6i** deriving from the Mukaiyama–Michael-type addition/heterocyclization reaction of silyl enol ether **2g** on 1,2-diaza-1,3-butadiene **1b** (Scheme 5). This different behavior is attributable to the different acidity of the protons in the α-position at the −C=N− moiety of the hydrazonic adduct intermediates. The simple procedure described here may be useful for the synthesis of several natural products. As a matter of fact, the indole ring is frequently present in several natural structures: the spectrum of indole alkaloids appears perhaps that most largely known.[20]



Scheme 5. Synthesis of indole derivatives **7a,b** through Mukaiyama–Michael-type addition/heterocyclization/aromatization reaction of 2-(trimethylsilyloxy)-1,3-cyclohexadiene **2g** on 1,2-diaza-1,3-butadienes **1a,b**.

Conclusions

In conclusion, we here describe a new facile and versatile approach to 1-aminopyrrol-2-ones and 1-aminopyrroles from 1,2-diaza-1,3-butadienes **1a,b** and silyl ketene acetals **2a,b** or silyl enol ethers **2c–f**, in the presence of a catalytic amount of Lewis acids. The mechanistic investigations demonstrate that this Mukaiyama–Michael-like reaction proceeds *via* coordination by Lewis acid of enolsilyl derivative and its conjugate 1,4-addition on the azo-ene system of 1,2-diaza-1,3-butadienes. The thermodynamically driven migration of the silyl group from hydrazonic to amidic nitrogen seems to proceed *via* an intermolecular transfer. Moreover, its acidic cleavage and the final internal heterocyclization give the final 1-aminopyrrol-2-ones **5** and 1-aminopyrroles **6**. The synthesis of 1-aminoindoles **7a,b** by addition of 2-(trimethylsilyloxy)-1,3-cyclohexadiene **2g** on 1,2-diaza-1,3-butadienes **1a,b**, followed by a dehydrogenation-aromatization process to give indole derivatives is also reported. Thus, we report here an one-pot procedure able to provide highly functionalized pyrrole and indole derivatives useful for subsequent structural modifica-

tions. Further investigations are presently in progress in order to extend the scope of these reactions.

Experimental Section

General Remarks

All of the commercially available reagents and solvents were used without further purification. 1,2-Diaza-1,3-butadienes **1a,b** were synthesized as a mixture of *E/Z* isomers[11] as previously reported.[21,22] Melting points were determined in open capillary tubes and are uncorrected. FT-IR spectra were obtained as Nujol mulls. Mass spectra were recorded on a Shimadzu GC-MS QP5050 A spectrometer (70 eV) and HR-MS were recorded on a Thermo Finnigan Mat95XP apparatus. All ^{1}H NMR and ^{13}C NMR spectra were recorded at 400 and 100.64 MHz, respectively. Proton and carbon spectra were referenced internally to solvent signals, using values of $\delta = 2.49$ ppm for proton (middle peak) and $\delta =$ 39.50 ppm for carbon (middle peak) in DMSO-d_6 and $\delta =$ 7.26 ppm for proton and $\delta = 77.00$ ppm for carbon (middle peak) in $CDCl_3$. Coupling constants (*J*) are given in Hz. Precoated silica gel plates 0.25 mm were employed for analytical thin-layer chromatography and silica gel 60 Å (35–70 μm) for column chromatography.

General Procedure for the Mukaiyama–Michael-Type Addition of Silyl Ketene Acetals 2a,b and Silyl Enol Ethers 2c–g on 1,2-Diaza-1,3-butadienes 1a,b

Under a nitrogen atmosphere, to a solution of 1,2-diaza-1,3-butadienes **1a,b** (1.0 mmol) in CH_2Cl_2 (6 mL) the silyl ketene acetals **2a,b** or the silyl enol ethers **2c–g** (1.2 mmol) and $ZnCl_2$ (0.2 mmol) were added. The mixture was stirred at room temperature for the time indicated (see footnote [a] of Tables 2 and 3), and then the reaction mixture was quenched with few drops of TFA in the case of the reactions between **1a,b** and **2a,c–g** or with TBAF (1 M solution in THF, 1 mmol) in the case of reaction between **1a,b** and **2b**. Compounds **4a–e** and **6a–i** were obtained by chromatography on silica gel column. In order to obtain the products **3a–d** and **4f**, the crude mixture was directly purified by chromatography on silica gel column (see Supporting Information).

Crossover Experiment for the Mukaiyama–Michael-Type Reaction of Silyl Ketene Acetals 2a and 2b on 1,2-Diaza-1,3-butadiene 1a

Under a nitrogen atmosphere, to a solution of 1,2-diaza-1,3-butadiene **1a** (1.0 mmol) in CH_2Cl_2 (6 mL) the silyl ketene acetals **2a** and **2b** (1.2 mmol) and $ZnCl_2$ (20 mol%) were added. The mixture was stirred at room temperature until complete disappearance of 1,2-diaza-1,3-butadiene **1a** (10 min, monitored by TLC), and then the crude reaction mixture was directly purified by chromatography on silica gel column (elution mixture: cyclohexane/ethyl acetate, 75:25), thus isolating **3a,c,e,f**.

Procedure for the Synthesis of 5a,b Starting from 4a,b

Sodium methoxide (1 mmol) was added to a solution of compounds **4a,b** (1 mmol) in 50 mL of methanol. Then the solution was refluxed until the reaction was completed (12 h, monitored by TLC). The reaction mixture was concentrated under reduced pressure. Products **5a,b** were isolated by chromatography on silica gel column with ethyl acetate (see Supporting Information).

Procedure for the Synthesis of 7a Starting from 4f

To a solution of compound **4f** (1 mmol) in THF (15 mL) few drops of TFA were added: the solution was stirred at room temperature until complete disappearance of starting material (24 h, monitored by TLC). The solvent was removed under reduce pressure, and the crude reaction mixture was purified by chromatography on silica gel (elution mixture: ethyl acetate/methanol, 95:5). Product **7a** was crystallized from ethyl acetate/methanol (see Supporting Information).

Procedure for the Synthesis of 7b Starting from 6i

To a solution of compound **6i** (1 mmol) in EtOH (15 mL) Pd/C (110 mg, 5%) was added and the mixture refluxed until complete disappearance of starting material (3 h, monitored by TLC). The mixture was filtered and the solvent evaporated under reduced pressure. Product **7b** was isolated by chromatography on silica gel (elution mixture: ethyl acetate/cyclohexane, 60:40) and crystallized from ethyl acetate (see Supporting Information).

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