Organozinc α-Diimine Radicals. Synthesis and Reactivity toward Alkyl Halides

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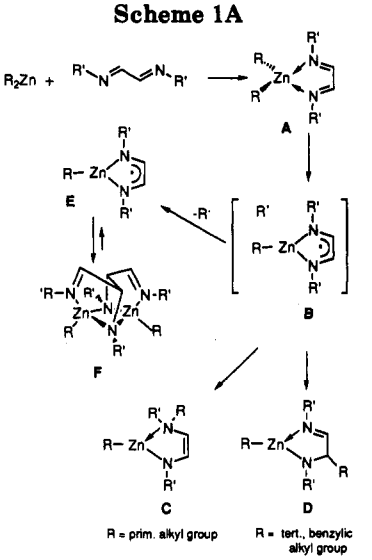
Organozinc radicals, [RZn-*t*-BuDAB]•, which are considered to be key intermediates in the regioselective alkylation reactions of R_2Zn compounds with 1,4-di-*tert*-butyl-1,4-diaza-1,3-butadiene (*t*-BuDAB), have been prepared *via* independent routes in good yield either from the reaction of K(*t*-BuDAB) with RZnCl or by the thermal conversion of stable R_2Zn-*t*-BuDAB complexes (R = Me, CH_2SiMe_3). In solution the [RZn-*t*-BuDAB]• radicals are in equilibrium with their C–C coupled dimers, which were isolated as solids. A preliminary X-ray diffraction study of one such dimer, **6a**, shows the stereoselective coupling of two Me_3SiCH_2Zn-*t*-BuDAB moieties by a C–C bond. The [RZn-*t*-BuDAB]• radicals are reactive toward alkyl halides, like allyl and benzyl bromide, as well as α- and β-substituted halo esters, producing C-alkylated products in good yield. The reactions with the halo esters give, after a subsequent ring closure reaction, heterocyclic products, *i.e.* β-lactams (with good to excellent diastereoselectivity, de 60–90%) and 2-pyrrolidinones.

Introduction

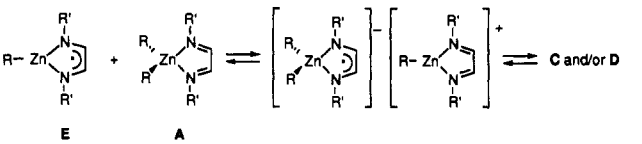
For several years it has been known that 1,4-disubstituted 1,4-diaza-1,3-butadienes (R′N=CH—CH=NR′ (R′DAB)) are alkylated with high regioselectivity by dialkylzinc compounds.[1] The reaction of R′DAB with primary dialkylzinc compounds results in quantitative alkylation at a nitrogen atom of the DAB skeleton, affording β-amino zinc—enamides, whereas in the reactions of R′DAB with tertiary and benzylic zinc compounds exclusively C-alkylated products are obtained. An extensive study concerning the mechanism of these remarkable alkylation reactions revealed that a radical type of mechanism is involved. Two possible mechanisms have been put forward. The initial step in both is the formation of a thermally instable 1:1 coordination complex R_2-ZnR′DAB (**A**) that, as a consequence of intramolecular ligand (R) to ligand (R′DAB) charge transfer, is activated for further thermal (or photochemical) conversion.[1c,d] In the first proposal (see Scheme 1A), this coordination complex undergoes a homolytic alkyl—zinc bond cleavage, leading to the radical pair [RZn(R′DAB)]•R• (**B**) in a solvent cage. Collapse of these radicals leads to alkylation of the chelating DAB ligand, resulting in the formation of N- (**C**) or C-alkylated (**D**) products.

In the second mechanistic proposal (Scheme 1B) a steady state concentration of the organozinc radical of **B** is present, which reacts with the initial 1:1 complex **A** to give a diorganozinc radical-anion and monoorganozinc cation pair, $[R_2ZnR'DAB]^{\bullet-}/[RZnR'DAB]^+$. Alkyl group

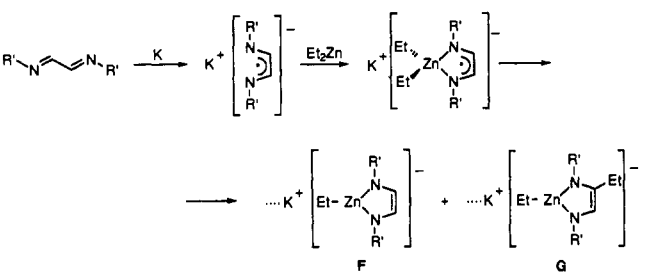
Scheme 1A



Scheme 1B



Scheme 1C



transfer between the zinc centers within this pair gives the N- or C-alkylated products and regenerates the corresponding organozinc radical **B**.[2] This mechanism,

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(1) (a) Klerks, J. M.; Jastrzebski, J. T. B. H.; van Koten, G.; Vrieze, K. *J. Organomet. Chem.* **1982**, *224*, 107. (b) van Koten, G. In *Organometallics in Organic Synthesis*; de Meijere, A., tom Dieck, H., Eds.; Springer-Verlag; Berlin, 1987; p 277. (c) Kaupp, M.; Stoll, H.; Preuss, H.; Kaim, W.; Stahl, T.; van Koten, G.; Wissing, E.; Smeets, W. J. J.; Spek, A. L. *J. Am. Chem. Soc.* **1991**, *113*, 5606.

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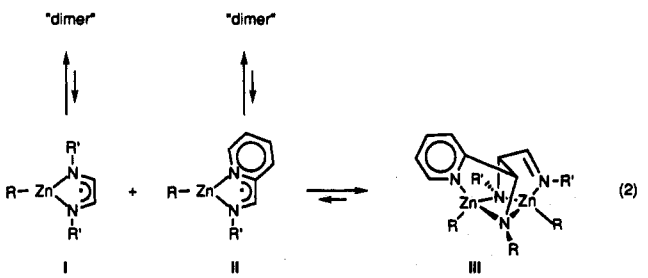
however, seems less likely, as we have recently found that independently synthesized [$R_2ZnR'DAB$]K radical anionic salts collapse readily via alkyl group transfer to the organodiamidozincates **F** and **G** (see Scheme 1C).

ESR measurements of the reaction mixture at room temperature, after **A** had been converted to **C** and **D**, showed the presence of the persistent organozinc radical [$RZnR'DAB$]$^\bullet$ (**E**) in low concentrations.[3] Radical **E** is formed from **B** by escape of the alkyl radical from the solvent cage. Similar radical species have been observed earlier by Clopath and von Zelewski[4] for [$XZnR'DAB$]$^\bullet$ (X = Cl, Br, I, CN).

We have been able to prepare the organozinc radicals **E** independently from 1:1 reactions of organozinc halides (RZnCl) with the potassium derivatives of R'DAB as crystalline solids in good yield. This enabled the study of the structural features and reactivity of these interesting species. Cryoscopic molecular weight determinations and NMR studies indicated that in solution these organozinc radicals are in equilibrium with their dimers. The latter consists of two radicals which are coupled *via* a C–C bond. The concentration of monomeric radicals **E** in the equilibrium is very small. The absence of line broadening in the NMR spectra, in which only the diamagnetic dinuclear species is visible, indicates that the association and dissociation rates (k_1 and k_{-1}) are small compared with the rate of the NMR experiment (see eq 1). The existence

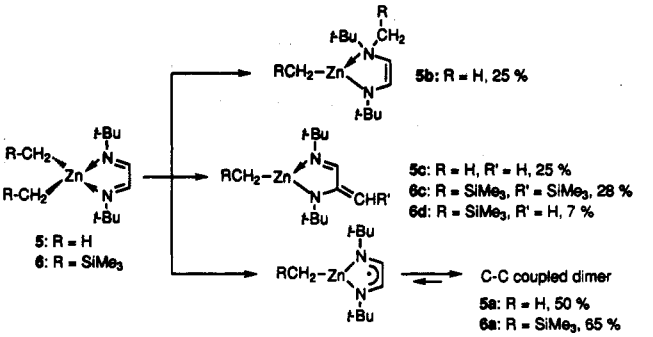
$$2\,[RZnR'DAB]^\bullet \underset{k_{-1}}{\overset{k_1}{\rightleftharpoons}} [RZnR'DAB]_2 \qquad (1)$$

of this equilibrium was confirmed by the observation that upon mixing of two different symmetric C–C coupled dimers (**I** and **II**) a third unsymmetric dimer (**III**) was detected by ^1H NMR. The ratio of the dimers (**I**:**II**:**III**) was found to be the statistical ratio 1:1:2 (see eq 2).[3b] The



first isolated and crystallized organozinc radical dimer of this type was [EtZn-*t*-BuPyca]$_2$ (**1a**) (*t*-BuPyca = *t*-Bu—N=CH-2-C_5H_4N).[3b,5] The characteristic C—C coupled dimeric structure of two former diimine skeletons was first observed in [$(Mo(CO_3))_2$(*t*-BuDAB)$_2$][6a] and [Ru_2-$(CO)_5$(*t*-BuDAB)$_2$][6b] and was later found in [$Mn_2(CO)_6$-(*t*-BuDAB)$_2$][6c] as well.

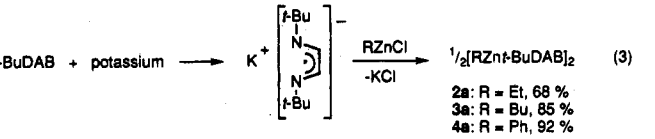
Scheme 2



In this paper we present the results of a study of the synthesis and structural features of such dinuclear organozinc α-diimine species, the equilibria in which they are involved, and their reactivity toward alkyl halides. The independent synthesis, isolation, and reactivity of the diorganozincate radical/organozinc cation species will be reported separately.[2]

Results

Synthesis of the Dinuclear Species. The reaction of the potassium salt of *t*-BuDAB radical anion K(*t*-BuDAB), with 1 equiv of RZnCl gives rise to the formation of dinuclear species [RZn-*t*-BuDAB]$_2$, which can be isolated in moderate to good yields (see eq 3). These



reactions have been carried out on a 5–50-mmol scale.

In contrast to other R_2Zn(α-diimine) (α-diimine = R'DAB, R'Pyca) complexes, which undergo thermal conversion already at low temperatures, the diorganozinc complexes Et_2Zn-*t*-BuPyca (**1**), Me_2Zn-*t*-BuDAB (**5**), and $(Me_3SiCH_2)_2Zn$-*t*-BuDAB (**6**) are stable at room temperature. This allowed the synthesis of the dinuclear species **1a**, **5a**, and **6a** by the thermal conversion of the respective 1:1 coordination complexes **1**, **5**, and **6**. When solutions of these complexes in benzene are heated at 70 °C for 6 h, the dinuclear species [MeZn-*t*-BuDAB]$_2$ (**5a**) and [Me_3-$SiCH_2Zn$-*t*-BuDAB]$_2$ (**6a**) are formed, which were isolated in acceptable yields (45% and 56%, respectively) after crystallization. Two further products were identified in the product mixture obtained after heating of **5**, *i.e.* [MeZn-(*t*-BuN—CH=CH—N(Me)-*t*-Bu)] (**5b**; 25%) and [MeZn-(*t*-BuN=CH—$C(CH_2)$—N-*t*-Bu)] (**5c**; 25%). These species have been identified in an earlier study of **5** in solution.[7] The thermal decomposition reaction of **6** yielded, in addition to **6a**, the secondary products [Me_3SiCH_2Zn(*t*-BuN=CH—$C(CH_2)$—N-*t*-Bu)] (**6c**; 27%, similar to **5c**) and [Me_3SiCH_2Zn(*t*-BuN=CH—$C(CHSiMe_3)$—N-*t*-Bu)] (**6d**; 7%). These species have also been identified previously.[7]

The dinuclear organozinc–diamido–diimino compounds (**1a**–**6a**) are stable for long periods at ambient temperatures, when stored under a nitrogen atmosphere. Upon hydrolysis, the aliphatic organic diamino–diimino C–C

(2) We have preliminary indications that ionic organozinc cation/radical-anion species are key intermediates in the alkylation reactions of R_2Zn with R'DAB; Wissing, E.; Kaupp, M.; Boersma, J.; Spek, A. L.; van Koten, G. *Organometallics* **1994**, *13*, 2349.

(3) (a) Jastrzebski, J. T. B. H.; Klerks, J. M.; van Koten, G.; Vrieze, K. *J. Organomet. Chem.* **1981**, *210*, C49. (b) van Koten, G.; Jastrzebski, J. T. B. H.; Vrieze, K. *J. Organomet. Chem.* **1983**, *250*, 49.

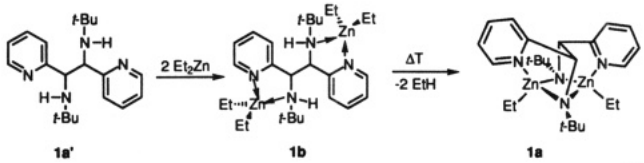
(4) Clopath, P.; von Zelewsky, A. *Helv. Chim. Acta* **1972**, *55*, 52.

(5) Spek, A. L.; Jastrzebski, J. T. B. H.; van Koten, G. *Acta Crystallogr.* **1987**, *C43*, 2006.

(6) (a) Staal, L. H.; Oskam, A.; Vrieze, K.; Roosendaal, E.; Schenk, H. *Inorg. Chem.* **1979**, *18*, 1634. (b) Staal, L. H.; Polm, L. H.; Balk, R. W.; van Koten, G.; Vrieze, K.; Brouwers, A. M. F. *Inorg. Chem.* **1980**, *19*, 3343. (c) Keijsper, J.; van Koten, G.; Vrieze, K.; Zoutberg, M.; Stam, C. H. *Organometallics* **1985**, *4*, 1306.

(7) Wissing, E.; Rijnberg, E.; van der Schaaf, P. A.; van Gorp, K.; Boersma, J.; van Koten, G. *Organometallics*, following article in this issue.

coupled products are formed which, however, are unstable and decompose instantly, except for **1a**, which upon hydrolysis affords the stable organic product **1a′**. Compound **1a** was regenerated quantitatively by treatment of **1a′** with 2 equiv of Et_2Zn. At first, the thermally unstable coordination complex $[Et_2Zn(C_5H_4N\text{-}2\text{-}CH\text{-}NH\text{-}t\text{-}Bu)]_2$ (**1b**) is formed, which on heating to 50 °C converts to **1a** (see eq 4).



(4)

A preliminary X-ray structure determination was carried out on **6a**.[8] The structure of **6a** is comparable to that of **1a**, in which two 2-pyridyl units are present instead of the two neutral imine functions.

Spectroscopic Analysis of the Dimeric Species. Since the equilibria between the dinuclear species and the mononuclear organozinc radicals lie far to the side of the dinuclear species and the rate constants k_1 and k_{-1} (see eq 1) are small, it was possible to study the equilibria by both NMR and ESR spectroscopy (cf. ref 1c).

The ^1H NMR spectra of the aliphatic dimers (**2a–6a**) in all cases show a doublet between 2.64 and 2.73 ppm (^3J = 2.6–2.8 Hz) for the protons bonded to the bridging carbon atoms, and between 7.59 and 8.14 ppm for the imine proton (^3J = 2.6–2.8 Hz). The diastereotopicity of the methylene protons of the zinc-bonded Et, Bu, and CH_2SiMe_3 groups in **1a–3a** and **6a** is evident from the ^1H NMR spectra. This is a result of the fact that both the bridging C atoms and the zinc atoms in these dimers are stereogenic centers.

The ESR spectra of several [RZn-*t*-BuDAB]• radicals (R = Me, Et, *i*-Pr, and *t*-Bu) have been published.[1] Only small differences between the $^{14}N(1,4)$ and $^1H(2,3)$ splittings of the 1,4-diaza-1,3-butadiene ligands in these organozinc radicals had been observed. The α-protons of the alkyl group bonded to the zinc atom show a small additional hyperfine splitting; see Figure 1a. The ESR spectra of the organozinc radicals [Me_2SiCH_2Zn-*t*-BuDAB]• and [$CH_3(CH_2)_3$Zn-*t*-BuDAB]• show the same splitting pattern as was observed for the [EtZn-*t*-BuDAB]• radical, although some of the a_x constants differ (see Table 1). The ESR spectrum of the [PhZn-*t*-BuDAB]• radical (see Figure 1b) is similar to that observed earlier for the [*t*-BuZn-*t*-BuDAB]• radical: both compounds lack the α-hydrogens at C_{ipso} and C_a, respectively.[1c] The uncomplicated hyperfine pattern is caused by coupling with the ^1H and ^{14}N nuclei of the DAB ligand only, and additional coupling with aryl ring protons is not observed. The spectrum of the [EtZn-*t*-BuPyca]• radical is very complex because of super hyperfine splitting with the pyridyl ring protons, and so far no reliable assignment has been possible.

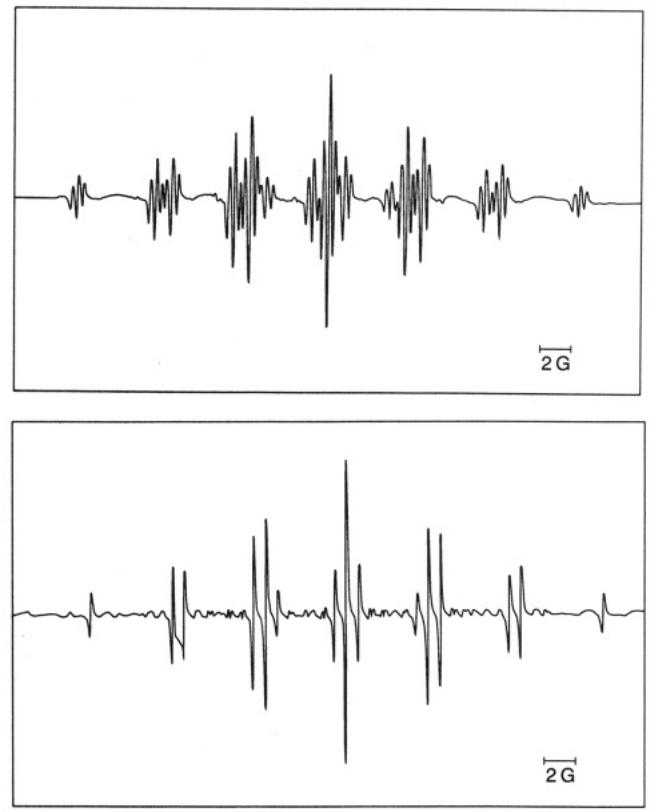


Figure 1. ESR spectra of the radical complexes (a, top) [Me_3SiCH_2Zn*t*-BuDAB]• and (b, bottom) [PhZn*t*-BuDAB]•.

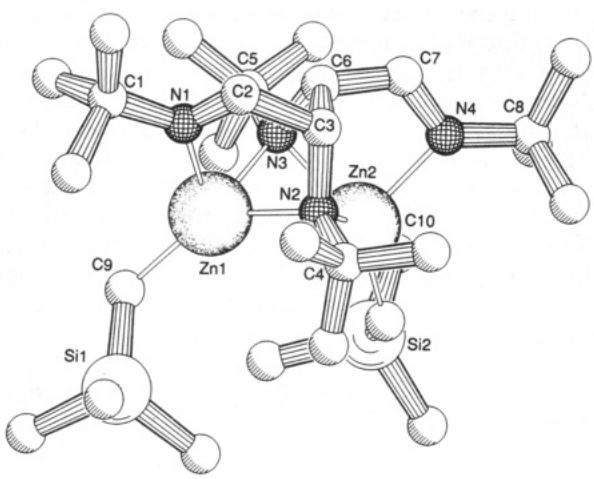
Table 1. ESR Data for [RZn-*t*-BuDAB]• Radicals[a,b]

[RZn-*t*-BuDAB]• R group	$a(^{14}N)$	$a(^1H)$	$a(x)^c$
CH_2SiMe_3	0.496	0.593	0.038
Et[d]	0.491	0.585	0.043
Ph	0.505	0.595	
t-Bu[e]	0.508	0.578	

[a] In mT (1 mT = 10 G). [b] Measurements in diethyl ether at room temperature. [c] Hyperfine splitting caused by protons at the α-carbon of the R group bonded to zinc. [d] Ref 3a. [e] Ref 1c.

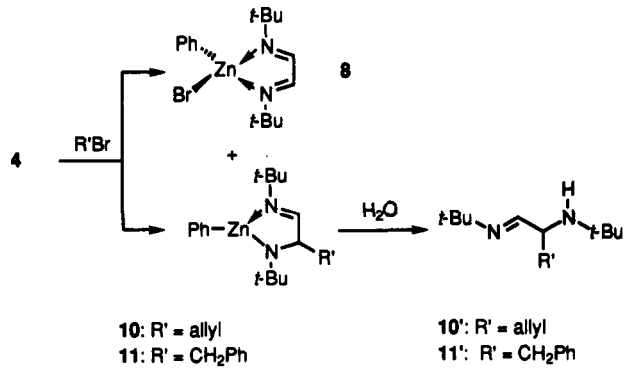
Alkylation Reactions. The equilibrium between the organozinc radicals and their dinuclear species is temperature dependent. When the temperature is raised, the equilbrium shifts toward the side of the radical, as indicated by an enhancement of the intensity of the ESR

(8) The refinement of the X-ray data was hampered by twinning and the *R* value could not be reduced below 14%. Nevertheless the chemical structure is certain and compound **6a** consists of two [Me_3SiCH_2Zn-*t*-BuDAB] units, which are stereoselectively coupled *via* a new C–C bond (C(2)–C(3)):

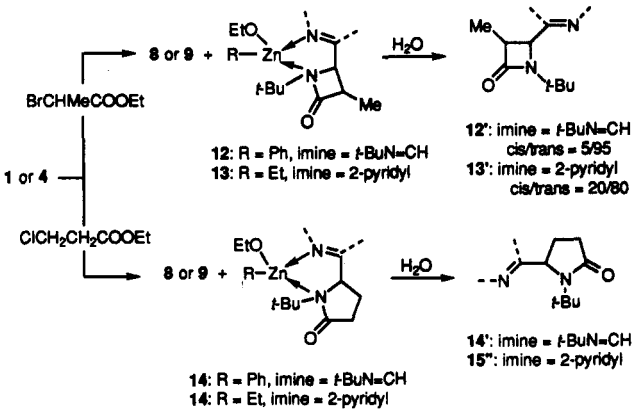


The so-formed molecule acts as a quadridentate dianionic ligand in which each of the two neutral imine N atoms coordinates to a zinc atom and both monoanionic amido N atoms bridge between the two Me_3SiCH_2Zn moieties, completing four-coordination at each of the two zinc atoms. The newly formed C–C bond is significantly longer (1.62 Å) than a normal $C(sp^3)$–$C(sp^3)$ single bond. Such bond elongation has been reported earlier in compounds containing two C–C coupled DAB groups[6] and seems to be characteristic for C–C bonds in N–C–C–N moieties in which both nitrogens are covalently bonded to metal centers.

Scheme 3



Scheme 4



signal and a deepening of the color of the solution. It appears that at higher temperatures these organozinc radicals have a useful reactivity toward reactive alkyl halides (R'X), like allyl bromide, benzyl bromide, ethyl 2-bromopropionate, and ethyl 3-chloropropionate.

The dinuclear species (EtZn-*t*-BuDAB)$_2$ (**2a**) and (BuZn-*t*-BuDAB)$_2$ (**3a**) could not be used in the alkylation reactions, since they are thermally unstable. In a separate experiment we have found that **2a** and **3a** decompose at 80 °C into *t*-BuDAB (50%), the N-alkylated product RZn [*t*-BuNCH=CHN-*t*-Bu(R)] (50%), and metallic zinc. However, the [EtZn-*t*-BuPyca]$_2$ (**1a**) and [PhZn-*t*-BuDAB]$_2$ (**4a**) dimers are stable at 80 °C and can be used in the alkylation reaction with alkyl halides.

The reactions of **4a** with R'X (R'X = (allyl)Br or PhCH$_2$Br) were performed in benzene at 80 °C at a dimer:alkyl halide molar ratio of 1:1 and reached completion in 6 h. The reactions gave a mixture of 50% of the coordination complex PhZnBr(*t*-BuDAB) (**8**) and 50% of the C-alkylated compounds PhZn(*t*-BuN—CHR—CH=N-*t*-Bu) (R = allyl (**10**), R = PhCH$_2$ (**11**)). The large difference in solubility of the two types of products (**8** *versus* **10** and **11**) in hexane allowed an easy separation. The hydrolysis of **10** and **11** gave the organic products **10'** and **11'** in good to excellent yield, >90% (see Scheme 3).

The dinuclear species **1a** and **4a** react with the α-substituted bromo ester BrCHMeCOOEt in 16 h to give complexes **12** and **13**, in which a heterocyclic β-lactam moiety coordinates to PhZnOEt and EtZnOEt, respectively, as well as complexes PhZnBr(*t*-BuDAB) (**8**) and EtZnX(*t*-BuPyca) (X = Cl, Br) (**9**), respectively (see Scheme 4). Similar reactions with the β-substituted chloro ester ClCH$_2$CH$_2$COOEt resulted in the 2-pyrrolidinone complexes of EtZnOEt (**14**) and PhZnOEt (**15**) (see Scheme 4). After hydrolysis the free ligands (**12'**–**15'**) were isolated in good yields. The β-lactams were predominantly formed in the *trans* configuration, the de being 90% for **12'** and 60% for **13'**.

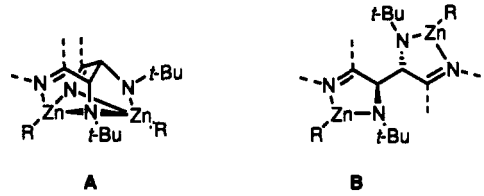


Figure 2. Representation of the two possible conformations of the dinuclear [RZn(diimine)]$_2$ meso compound.

It must be noted that the yields of the alkylation products in these reactions are limited to a maximum of 50% (with respect to the starting material *t*-BuDAB and *t*-BuPyca), because of the formation of the coordination complexes **8** and **9**, respectively. The starting materials **1a** and **4a**, however, can be regenerated by treating **8** and **9** with 1 equiv of potassium.

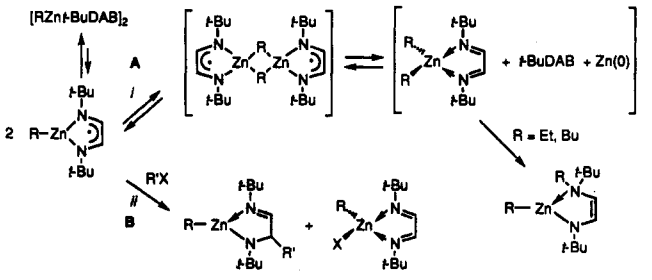
Discussion

Most coordination complexes of the type R$_2$Zn-*t*-BuDAB have limited thermal stability (decomposition temperatures range from −100 °C for R = *t*-Bu to −50 °C for R = Et) and rearrange quantitatively in a subsequent alkylation reaction into one (R = primary, tertiary alkyl or benzylic group) or at most two (R = secondary group) products (see Scheme 1).[1] Me$_2$Zn-*t*-BuDAB (**5**) and (Me$_3$SiCH$_2$)$_2$Zn-*t*-BuDAB (**6**), however, are stable at room temperature and homolytic R–Zn bond cleavage in **5** and **6** takes place only at about 35 °C. The so formed Me$^\bullet$ and Me$_3$SiCH$_2^\bullet$ radicals are highly mobile at that temperature, and accordingly, considerable radical escape from the solvent cage will take place, which is reflected by the lower yield of the DAB alkylation products. This leaves a large amount of organozinc radicals, that dimerize to the dinuclear species **5a** and **6a**.

The ^{1}H NMR spectra of all dinuclear species studied indicate that they are formed stereoselectively as one diastereoisomer, *i.e.* the (*R*)(*R'*)/(*S*)(*S'*) enantiomeric pair. Formation of a dinuclear compound containing the meso form (the (*R*)(*S'*)/(*S*)(*R'*) pair) was not observed. Study of molecular models showed that the quadridentate ligand in the meso compound cannot efficiently bind to a RZn pair. In that case an imine nitrogen has to act as a bridging atom between the two zinc atoms (see Figure 2A), which seems impossible, or the Zn–N bridges are not formed, resulting in the entropically less favorable unsymmetric compound, of which the backbone is shown in Figure 2B.

Alkylation Reactions. The dimers [RZn-*t*-BuDAB]$_2$, R = Et (**2a**), R = Bu (**3a**), could not be used in alkylation reactions with alkyl halides because of their instability at temperatures of above 40 °C. At these temperatures probably a disproportionation reaction occurs, leading to metallic zinc, *t*-BuDAB, and the N-alkylated product. We believe that a transient intermediate (see Scheme 5, route A) is formed in which the R groups bridge the zinc atoms of two Zn-*t*-BuDAB moieties. A complete alkyl group transfer from one zinc to the other can take place in this species with a consecutive electron shift, which leads to the formation of R$_2$Zn-*t*-BuDAB as well as metallic zinc and *t*-BuDAB. Under these conditions the coordination complex R$_2$Zn-*t*-BuDAB undergoes a direct alkyl transfer

Scheme 5



I. above 40 °C for **2a** and **3a**. *II.* above 80 °C for **1a** and **4a**.

from the zinc atom to a N atom of the chelating DAB. In contrast, when R = Ph, the reaction does not proceed beyond the formation of the thermally stable coordination complex Ph_2Zn-*t*-BuDAB. This allows its subsequent alkylation with alkyl halides, which require reaction temperatures above 50 °C (see Scheme 5, part B).

The alkylation reactions of **4a** with allyl and benzyl bromide are slow and give a yield of 50% (with respect to the amount of *t*-BuDAB starting material) of the alkylation products **10** and **11** (see Scheme 3). Similar C-alkylation reactions of *t*-BuDAB have been reported earlier by tom Dieck and co-workers.[9] Compound **11** may also be prepared in quantitative yield by reacting *t*-BuDAB with $(PhCH_2)_2Zn$ at room temperature.[10] The reactions of alkyl halides with the dinuclear species are of interest since the mononuclear organozinc radicals [RZnR'DAB]• are postulated as key intermediates in the alkylation reactions of R_2Zn with R'DAB. However, in the latter reactions the alkyl radical is formed within the inner sphere of the organozinc radical and the radical pair collapses by attack of the alkyl radical at the [RZnR'DAB]• radical (*vide supra*). However, in the here presented alkylation of organozinc radicals a free alkyl group is involved. The differences in product formation between inner- and outer-sphere radical reactions is best observed in the reactions with the β-substituted halo ester $ClCH_2CH_2COOEt$. This has a primary carbon halogen bond which results in C alkylation, whereas the primary dialkylzinc compound $Zn(CH_2CH_2COOEt)_2$ gives N alkylation in the reaction with *t*-BuDAB (*vide supra*). Thus, the heterocycles **12–15** are the result of initially formed C-alkylated products, which react further by an intramolecular nucleophilic attack of the amido nitrogen on the ester function. Subsequent elimination of EtZnOEt leads to the final β-lactam and 2-pyrrolidinone derivatives; see Figure 3. In a previous report we described the synthesis of **14'** *via* the direct reaction of $ClZn[CH_2CH_2COOEt]_2$ with *t*-BuDAB in 60% yield.[10]

The C-alkylated intermediates in the reactions leading to β-lactams are comparable with the ones we have observed in the synthesis of 3-amino-(4-imino)-2-azetidinones starting from α-amino ester enolates and α-diimines.[11] The final stereochemical outcome of the reaction between the [PhZn-*t*-BuDAB] radical and the α-bromo ester, *i.e.* the formation of a *cis*- and/or *trans*-β-lactam, is determined in the transition state of the C–C bond formation. The diastereoselective formation of the *trans*

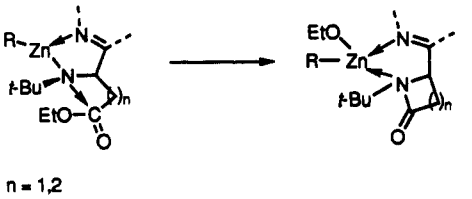


Figure 3. Cyclization reaction of the C-alkylated intermediate to the azetidinone ($n = 1$) (**12** and **13**) and 2-pyrrolidinone ($n = 2$) (**14** and **15**).

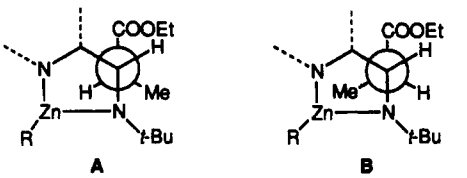
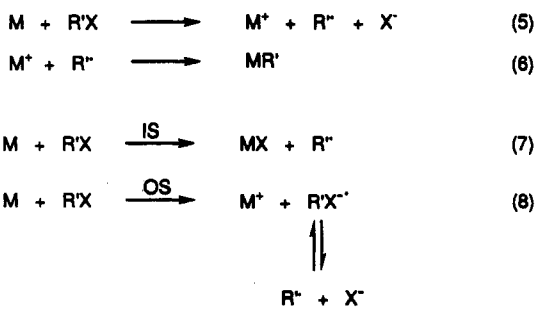


Figure 4. Newman projection along the incipient C–C bond leading to the precursor complexes of the β-lactams **12** and **13**: (A) C–C bond formation leading to cis β-lactam; (B) C–C bond formation leading to trans β-lactam.

stereoisomer, in our reaction, is mainly determined by steric effects, as is visualized in Figure 4.

We believe that a crucial step in the alkylation is the reaction of an alkyl radical with an organozinc radical (*vide infra*). The approach of the flat alkyl radical to the organozinc unit is less favored in the case of **A**, because of steric repulsion between the methyl group and the large *tert*-butyl group. When one of the *tert*-butylimine functions in **4a** is replaced by a pyridyl group as in **1a** the de of the *cis*- and *trans*-β-lactam formation slightly decreases, which is probably due to an increase of the steric constraints of the pyridyl group in **B** as compared with the single N=C group in **A**.

Mechanism of the Alkylation Reaction. Reactions of organometallic complexes (M) containing an unpaired electron, *e.g.* Ni(I),[12] Co(II),[13] and Cr(I)[14] complexes, with alkyl halides (R'X) have been extensively studied (see eqs 5 and 6). It was found that these complexes are oxidized



by alkyl halides, and this oxidation may proceed *via* an inner-sphere (IS) or outer-sphere (OS) electron transfer mechanism (see eqs 7 and 8, respectively). In most cases an outer-sphere mechanism was excluded by kinetic measurements.

The mechanism of the alkylation of organozinc radicals [RZnDAB]• with alkyl halides (R'X) is most probably comparable to the above mentioned oxidation reactions (see eqs 5–8). We propose as the first step in a single

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electron transfer (SET) from the organozinc species to the alkyl halide (eq 9). We believe that this SET reaction

$$[RZnDAB]^{\cdot} + R'X \longrightarrow [RZnDAB]^{+} + R'X^{-\cdot} \quad (9)$$

$$R'X^{-\cdot} \rightleftharpoons R'^{\cdot} + X^{-} \quad (10)$$

$$[RZnDAB]^{\cdot} + R'^{\cdot} \longrightarrow \text{alkylation products} \quad (11)$$

$$[RZnDAB]^{+} + X^{-} \longrightarrow RZnX(DAB) \quad (12)$$

can be considered as an outer-sphere electron transfer process. This is supported by the results of the He I/He II photoelectron spectroscopic studies of the organozinc radicals [RZn-*t*-BuDAB]• (R = Me, Et), by Louwen and Oskam,[15] that showed the low ionization energies of these radical species (6 eV). The so-formed radical-anion $R'X^{\cdot-}$ then dissociates to the radical R'• and anion X^- (eq 10), which subsequently react with the organozinc radical [RZnDAB]• and the organozinc cation $[RZnDAB]^+$, respectively, to form the alkylated product and RZnX(DAB) (see eqs 11 and 12).

Concluding Remarks

The organozinc radicals [RZn-*t*-BuDAB]•, which are important intermediates in the alkylation reactions of R_2Zn with *t*-BuDAB, are easily obtained by the reaction of K(*t*-BuDAB) with RZnCl or by the thermal decomposition of R_2Zn-*t*-BuDAB (R = Me, CH_2SiMe_3). The [RZn-*t*-BuDAB]• radicals are in equilibrium with their diamagnetic C–C coupled dinuclear species and crystallize as such. In solution the monomeric [RZn-*t*-BuDAB]• radicals react with alkyl halides to give C-alkylated products. In reactions with α- and β-substituted halide esters, C alkylation followed by a cyclization gives azetidinone and 2-pyrrolidinone derivatives, respectively. The azetidinones were obtained in a diastereomeric excess of 60–90%.

Experimental Section

General Information. All experiments were carried out under a dry and oxygen-free nitrogen atmosphere, using standard Schlenk techniques. Solvents were carefully dried and distilled from sodium/benzophenone prior to use. All starting chemicals were purchased from Aldrich Chemical Co. or Janssen Chimica. *N,N'*-Di-*tert*-butyl-1,4-diaza-1,3-butadiene (*t*-BuDAB)[16] and $[EtZn\text{-}t\text{-}BuPyca]_2$ (**1a**)[2] were prepared according to literature procedures. ^1H and ^{13}C NMR spectra were recorded on a Bruker AC-200 or Bruker AC-300 spectrometer in C_6D_6 at room temperature, using TMS as an external standard. ESR spectra were recorded on a Varian E-4 spectrometer. Boiling and melting points are uncorrected. Elemental analyses were performed by the Institute of Applied Chemistry (TNO), Zeist, The Netherlands, and by Dornis und Kolbe, Mikroanalytisches Laboratorium, Müllheim a.d. Ruhr, FRG.

General Procedure for the Synthesis of $[RZn\text{-}t\text{-}BuDAB]_2$ (R = Et (2a), R = Bu (3a), and R = Ph (4a)). To a stirred solution of *t*-BuDAB (8.4 g, 50 mmol) in THF (75 mL) was added 1 equiv of potassium (1.95 g, 50 mmol) in small lumps. After stirring for 16 h, the resulting brown suspension was cooled to 0 °C and a solution of 1 equiv of RZnCl (R = Et, Bu, Ph) in Et_2O was added. The suspension was stirred for an additional 10 min at room temperature. Subsequently, the solvent was removed *in vacuo* and the resulting solid was extracted with warm hexane (4 × 50 mL). The solvent of the combined hexane extracts was evaporated to dryness, affording the crude products as yellow solids in 8.9-g (68%) (**2a**), 12.3-g (85%) (**3a**), and 14.3-g (92%) (**4a**) yields, respectively. Repeated crystallization from hexane afforded the products as white solids. ^1H NMR of **2a**: δ 7.65 (d, J = 2.8 Hz, 2H, N=C*H*), 2.73 (d, J = 2.8 Hz, 2H, NC*H*), 1.86 (t, 6H, $ZnCH_2CH_3$), 1.09 (s, 18H, $C(CH_3)_3$), 1.02 (s, 18H, $C(CH_3)_3$), 0.78 (dq, 4H, $ZnCH_2CH_3$). ^{13}C NMR of **2a**: δ 170.7 (N=CH), 60.1 (NCH), 57.4, 51.7 ($C(CH_3)_3$), 32.7, 29.5 ($C(CH_3)_3$), 14.5 ($ZnCH_2CH_3$), 2.1 ($ZnCH_2CH_3$). ^1H NMR of **3a**: δ 7.63 (d, J = 2.9 Hz, 2H, N=C*H*), 2.71 (d, J = 2.9 Hz, 2H, NCH), 2.06 (m, 4H, $ZnCH_2CH_2CH_2CH_3$), 1.79 (m, 4H, $ZnCH_2CH_2CH_2CH_3$), 1.22 (t, 6H, $ZnCH_2CH_2CH_2CH_3$), 1.09 (s, 18H, $C(CH_3)_3$), 1.02 (s, 18H, $C(CH_3)_3$), 0.77 (dt, 4H, $ZnCH_2CH_3$). ^{13}C NMR of **3a**: δ 170.7 (N=CH), 60.1 (NCH), 54.6, 51.8 ($C(CH_3)_3$), 33.2 (CH_2CH_3), 32.7 ($C(CH_3)_3$), 31.1 ($ZnCH_2CH_2$), 21.2 ($C(CH_3)_3$), 14.5 (CH_2CH_3), 11.2 ($ZnCH_2$). Anal. Calcd for $C_{28}H_{58}N_4Zn_2$: C, 57.83; H, 10.04; N, 9.63. Found C, 58.04; H, 9.95; N, 9.48. ^1H NMR of **4a**: δ 8.14 (m, 4H, phenyl), 7.65 (d, J = 2.8, 2H, N=C*H*). 7.45–7.23 (m, 6H, phenyl), 2.75 (d, J = 2.8 Hz, 2H, NC*H*), 1.08 (s, 18, $C(CH_3)_3$), 1.05 (s, 18H, $C(CH_3)_3$). ^{13}C NMR of **4a**: δ 171.2 (N=CH), 140.4, 128.4, 127.6, 125.8 (phenyl), 59.8 (NCH), 58.2, 52.2 ($C(CH_3)_3$), 32.9, 29.6 ($C(CH_3)_3$). Anal. Calcd for $C_{32}H_{50}N_4Zn_2$: C, 61.84; H, 8.11; N, 9.01. Found: C, 62.71; H, 8.18; N, 9.12.

$[MeZn\text{-}t\text{-}BuDAB]_2$ (5a). To a stirred solution of *t*-BuDAB (1.68 g, 10 mmol) in benzene (20 mL) was added 1 equiv of Me_2Zn (10 mL of a 1 M solution in hexane). The resulting red suspension was heated for 6 h at 70 °C. The solvent was evaporated *in vacuo*, leaving a brown oil. The oil was dissolved in hexane (15 mL) and stored at −20 °C to give **5a** as white crystals, yield 2.23 g (45%). ^1H NMR of **5a**: δ 7.61 (d, J = 2.8 Hz, 2H, N=C*H*), 2.72 (d, J = 2.8 Hz, 2H, NC*H*), 1.08, 1.04 (s, 2 × 18H, $C(CH_3)_3$), −0.01 (s, 6H, $ZnCH_3$). ^{13}C NMR of **5a**: δ 170.8 (N=CH), 60.1 (NCH), 57.6, 52.2 ($C(CH_3)_3$), 32.6, 29.5 ($C(CH_3)_3$), −11.3 ($ZnCH_3$). Anal. Calcd for $C_{22}N_{46}N_4Zn_2$: C, 53.13; H, 9.32; N, 11.26. Found: C, 53.10; H, 9.38; N, 11.18.

Synthesis of $[Me_3SiCH_2Zn\text{-}t\text{-}BuDAB]_2$ (6a). To a stirred solution of *t*-BuDAB (10 mmol, 1.68 g) in benzene (20 mL) was added 1 equiv of $(Me_3SiCH_2)_2Zn$ (2.41 g, 10 mmol). The resulting purple suspension was heated for 6 h at 70 °C. The solvent was evaporated *in vacuo* leaving a brown oil. The oil was dissolved in hexane (15 mL) and stored at −20 °C to afford **6a** as white crystals, yield 3.6 g (56%). ^1H NMR of **6a**: δ 7.59 (d, J = 2.7 Hz, 2H, N=C*H*), 2.64 (d, J = 2.7 Hz, 2H, NC*H*), 1.12, 1.04 (s, 18H, $C(CH_3)_3$), 0.46 (s, 18H, $Si(CH_3)_3$), −0.32, −0.44 (dd, J = 12.3, 2 × 2H, $ZnCHH'Si(CH_3)_3$). ^{13}C NMR of **6a**: δ 171.42 (N=CH), 59.6 (NCH), 57.8, 52.4 ($C(CH_3)_3$), 32.8, 29.9 ($C(CH_3)_3$), 4.4 ($Si(CH_3)_3$), −3.4 ($ZnCH_2$). Anal. Calcd for $C_{28}H_{62}N_4Si_2Zn$: C, 52.40; H, 9.74; N, 8.73. Found: C, 51.93; H, 9.90; N, 8.85.

Hydrolysis of $[EtZn\text{-}t\text{-}BuPyca]_2$ (1a). To a stirred solution of **1a** (5.12 g, 10 mmol) in Et_2O (50 mL) was added H_2O (0.18 mL) at room temperature. The resulting suspension was stirred for 3 h and filtered off. The solvent of the filtrate was removed, affording **1a'** as a yellow solid in 3.19-g yield (98%). Compound **1a'** was crystallized from hexane to give a white solid; mp 85.5 °C. ^1H NMR of **1a'**: δ 8.38 (m, 2H, pyridyl), 7.34 (m, 2H, pyridyl), 7.09 (m, 2H, pyridyl), 6.62 (m, 2H, pyridyl), 4.25 (d, J = 4.72 Hz, 2H, NC*H*–C*H*N), 2.77 (d, J = 4.7 Hz, 2H, N*H*), 0.85 (s, 18H, $C(CH_3)_3$). ^{13}C NMR of **1a'**: 165.6, 148.5, 135.5, 123.3, 121.3 (pyridyl), 64.5 (NCH), 50.9 ($C(CH_3)$), 29.9 ($C(CH_3)_3$). Anal. Calcd for $C_{13}N_{23}N_2O$: C, 73.58; H, 9.26; N, 17.16. Found: C, 73.66; H, 9.30; N, 17.08.

Conversion of 1a' to 1a. Mixing of **1a'** with 2 equiv of Et_2Zn in diethyl ether at room temperature gives the coordination complex $[(Et_2Zn)_2(1a')]$, that slowly (4 h) converts to **1a** in quantitative yield. At 35 °C the formation of **1a'** is completed within 1 h.

General Procedure for the Alkylation Reaction. To a stirred solution of 10 mmol of an organozinc dimer (5.1 g of **1a** or 6.2 g of **4a**) in benzene (50 mL) was added 10 mmol of an appropriate alkyl halide R'X (allyl or benzyl bromide, ethyl

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2-bromopropionate, or ethyl 3-chloropropionate). The reaction mixture was heated at 80 °C for 6 h in the case of allyl and benzyl bromide and for 16 h in the case of ethyl 2-bromopropionate and ethyl 3-chloropropionate. After removing the solvent *in vacuo*, hexane (50 mL) was added. The solid ((EtZnBr(*t*-BuPyca) (**9**) in the case of **1a** and PhZnBr(*t*-BuDAB) (**8**) in the case of (**4a**)) was removed by centrifugation. The solid was extracted with cold hexane (2 × 10 mL). The combined solutions were treated with 20 mL of saturated aqueous ammonium chloride solution. The aqueous layer was separated and extracted with Et_2O (2 × 20 mL). The combined organic extracts were dried over Na_2SO_4 and concentrated *in vacuo* to afford the crude alkylated products. The products were purified by short way distillation (**10′** and **11′**) or by recrystallization (**12′–15′**).

The alkylation reaction with **4a** could also be performed as a one pot synthesis starting from *t*-BuDAB and potassium in THF (*vide supra*). After stirring for 10 h the mixture was treated with 1 equiv of PhZnCl and stirred for 10 min. The solvent was removed *in vacuo*, and subsequently, 50 mL of benzene and 1 equiv of R′X was added. The reaction mixtures were heated at 80 °C for the already indicated reaction times (given above). The alkylated products were obtained after normal workup procedures.

2,2-Dimethyl-3-aza-5-(*tert*-butylamino)-3,7-octadiene (10′): pale yellow oil, yield 1.91 g (91%); ^{1}H NMR δ 7.42 (d, *J* = 4.5 Hz, 1H, N=C*H*), 5.4 (m, 3H, C*H*=C*H*$_2$), 3.33 (m, 1H, NC*H*), 2.20 (m, 2H, C*HH′*CH=CH$_2$), 1.65 (br d, 1H, N*H*), 1.15, 1.02 (s, 9H, C(C*H*$_3$)$_3$); ^{13}C NMR (C_6D_6) δ 162 (N=CH), 136.1 (CH=CH$_2$), 116.9 (CH=CH$_2$), 57.8 (NCH), 56.2, 50.8 (*C*(CH$_3$)$_3$), 42.5 (*C*H$_2$ allyl), 40.6 (*C*H$_2$CH=CH$_2$), 29.7, 29.38 (C(C*H*$_3$)$_3$).

2,2,7,7-Tetramethyl-3,6-diaza-5-benzyl-3-octene (11′): Pale yellow oil, yield 2.52 g (97%) yield; ^{1}H NMR δ 7.47 (d, *J* = 4.6 Hz, 1H, N=C*H*), 7.09–7.24 (m, 5H, aryl), 3.60 (m, 1H, NC*H*), 2.79 (dd, ^2J = 13.2 Hz, ^3J = 5.9 Hz, 1H, C*HH′*—C_6H_5), 2.62 (dd, ^2J = 13.2 Hz, ^3J = 8.2 Hz, 1H, CH*H′*—C_6H_5), 1.67 (s, 1H, N*H*), 1.09, 0.95 (s, 9H, C(C*H*$_3$)$_3$); ^{13}C NMR (C_6D_6) δ 162.2 (N=*C*H), 139.1 (*ipso-C*), 130.1, 128.4, 126.5 (aryl), 58.2 (NCH), 56.3, 50.8 (*C*(CH$_3$)$_3$), 42.5 (*C*H$_2$ aryl), 30.0 (C(C*H*$_3$)$_3$), 29.6 (C(C*H*$_3$)$_3$). Anal. Calcd for $C_{17}H_{28}N_2$: C, 78.41; H, 10.84; N, 10.76. Found: C, 78.37; H, 10.93; N, 10.97.

***trans*-1-*tert*-Butyl-3-methyl-4-(*N*-*tert*-butylimino)azetidin-2-one (12′)**: white crystalline solid, yield 1.83 g (82%); crystallized from Et_2O at −20 °C; mp 65.5 °C; ^{1}H NMR δ 7.24 (d, *J* = 7.0 Hz, 1H, N=C*H*), 3.65 (dd, *J* = 7.0 Hz, *J* = 2.1 Hz, 1H, N=CH—C*H*), 2.56 (dq, *J* = 2.1 Hz, 7.3 Hz, 1H, COC(CH$_3$)*H*), 1.20, 1.07 (s, 9H, C(C*H*$_3$)$_3$), 1.04 (d, *J* = 7.3 Hz, 3H, COC(C*H*$_3$)H); ^{13}C NMR δ 167.4 (*C*=O), 156.5 (N=*C*H), 60.4 (NCH), 55.3, 52.2 (*C*(CH$_3$)$_3$), 46.2 (CO—*C*H(CH$_3$)), 27.7, 26.8 (C(*C*H$_3$)$_3$), 11.0 (CO—CH(*C*H$_3$)). Anal. Calcd for $C_{13}N_{23}N_2O$: C, 69.91; H, 10.38; N, 12.54. Found: C, 70.02; H, 10.86; N, 12.51.

***trans*- and *cis*-1-*tert*-Butyl-3-methyl-4-(2-pyridyl)azetidin-2-one (13′)**: white crystalline solid, yield 1.79 g (82%); pure *trans* diastereomer obtained as colorless crystals after repeated crystallization from Et_2O; ^{1}H NMR of **13′** *trans* diastereomer δ 8.38 (m, 1H, pyridyl), 6.95 (m, 2H, pyridyl), 4.18 (d, *J* = 2.1 Hz, 1H, NC*H*CHCH$_3$), 2.76 (dq, *J* = 2.1 Hz, *J* = 7.5 Hz, 1H, NCHC*H*CH$_3$), 1.17 (d, *J* = 7.5 Hz, 3H, NCH-CHC*H*$_3$), 1.15 (s, 9H, C(C*H*$_3$)$_3$); ^{13}C NMR δ 170.3 (*C*=O), 161.5, 149.6, 136.4, 122.6, 120.7 (pyridyl), 63.1 (NCH), 53.9, 53.1 (*C*(CH$_3$)$_3$), 28.1 (C(*C*H$_3$)$_3$), 13.1 (CH*C*H$_3$). Anal. Calcd for $C_{15}H_{18}N_2O$: C, 71.53; H, 8.31; N, 12.83. Found: C, 71.48; H, 8.42; N, 12.39. ^{1}H NMR of **13′** *cis* diastereomer: δ 8.38 (m, 1H, pyridyl), 6.95 (m, 2H, pyridyl), 4.73 (d, *J* = 5.9 Hz, 1H, NC*H*-CHCH$_3$), 3.13 (dq, *J* = 5.9 Hz, *J* = 7.6 Hz, 1H, NCHC*H*CH$_3$), 1.12 (s, 9H, C(C*H*$_3$)$_3$), 0.73 (d, *J* = 7.6 Hz, 3H, NCHCHC*H*$_3$). ^{13}C NMR of **13′** *cis* diastereomer: δ 170.1 (*C*=O), 159.5, 149.5, 135.6, 122.3, 121.9 (pyridyl), 59.0 (NCH), 53.7, 48.6 (*C*(CH$_3$)$_3$), 28.1 (C(*C*H$_3$)$_3$), 9.7 (CH*C*H$_3$).

1-*tert*-Butyl-5-(*tert*-butylimino)pyrrolidin-2-one (14′): white crystalline solid, isolated yield 1.95 g (87%); crystallized from Et_2O at −20 °C; mp 40 °C; ^{1}H NMR δ 7.28 (d, *J* = 6.2 Hz, 1H, N=C*H*), 4.09 (m, *J* = 8.5 Hz, *J* = 6.2 Hz, *J* = 1.4 Hz, 1H, N=C—C*H*), 2.29–1.94 (m, 2H, C*H*$_2$—C=O), 1.76–1.52 (m, 1H, C*HH′*—CH$_2$C=O), 1.41 (s, 9H, C(C*H*$_3$)$_3$), 1.35–1.09 (m, 1H, CH*H′*—CH$_2$C=O), 1.04 (s, 9H, C(C*H*$_3$)$_3$); ^{13}C NMR δ 174.5 (*C*=O), 158.3 (N=CH), 62.3 (NCH), 56.7, 54.3 *C*(CH$_3$)$_3$, 31.3 (*C*H$_2$—C=O), 29.3, 28.5 (C(*C*H$_3$)$_3$), 23.9 (*C*H$_2$—CH$_2$C=O). Anal. Calcd for $C_{13}H_{24}N_2O$: C, 69.60; H, 10.78; N, 12.49. Found: C, 68.09; H, 10.35; N, 12.25.

1-*tert*-Butyl-5-(2-pyridyl)pyrrolidin-2-one (15′): white crystalline solid, yield 1.83 g (84%); crystallized from Et_2O at −20 °C, mp 106.5 °C; ^{1}H NMR δ 8.38 (m, 1H, pyridyl), 6.97 (m, 1H, pyridyl), 6.78 (m, 1H, pyridyl), 6.57 (m, 1H, pyridyl), 4.72 (dd, *J* = 1.0 Hz, *J* = 8.4 Hz, 1H, NC*H*(pyridyl)—CH$_2$), 2.62–2.44 (m, 1H, COC*HH′*CHH′), 2.15–1.79 (m, 2H, CO—CH*H′*—C*HH′*), 1.48–1.36 (m, 1H, CO—CHH′—CH*H′*), 1.33 (s, 9H, C(C*H*$_3$)$_3$); ^{13}C NMR δ 175.2 (*C*=O), 164.3, 149.9, 136.5, 122.2, 119.9 (pyridyl), 63.6 (NCH), 54.5 (*C*(CH$_3$)$_3$), 31.1 (CH$_2$—*C*H$_2$—CO), 28.3 (C(*C*H$_3$)$_3$), 27.9 (CH$_2$—CH$_2$—CO). Anal. Calcd for $C_{13}N_{18}N_2O$: C, 71.53; H, 8.31; N, 12.83. Found: C, 71.62; H, 8.36; N, 12.77.

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