Theoretical Calculations of Chemical Interactions. Part 6.[1] An MNDO Study of the Intermediates Involved in CO Insertion into Lithium–Nitrogen Bonds in Lithium Dialkylamides

Norma S. Nudelman * **and Daniel G. Perez**
Departamento Quimica Organica, Facultad de Ciencias Exactas, Universidad de Buenos Aires, Pabellón II, Piso 3, Ciudad Universitaria, 1428 Buenos Aires, Argentina

Carbon monoxide insertion into Li–N bonds in lithium dialkylamides provides a useful synthetic method not only for substituted formamides but also for highly functionalized compounds such as substituted glyoxylamides and tartronamides. The high instability of the intermediates involved precludes direct independent determination of the various steps involved but theoretical calculations provide a way of predicting their feasibility. Both INDO and MNDO procedures have been used but the MNDO method has been found to be more appropriate for this study. The geometries and energies of the proposed intermediates have been calculated as well as the equilibrium positions for several acid–base equilibria and the energy changes involved in the different steps. An estimation of the solvent interaction with the charged intermediates has allowed a prediction of the temperature effect which is consistent with the observed experimental results.

The mechanistic aspects of insertion reactions of carbon monoxide into M–R bonds (R = H, alkyl, or aryl) is an area of intensive study and warrants attention from both experimental[2] and theoretical[3,4] considerations. Much effort has been devoted to the study of reactions involving transition metal complexes because of their obvious relevance as models for the Fischer–Tropsch process. In contrast, in spite of their great synthetic utility,[5–7] mechanistic studies on the reactions of CO with organolithium compounds have not yet appeared, with the exception of the calculation of the thermodynamic stabilities of carbonyl anions carried out by Schleyer[8] as part of expanded and critical theoretical research on organolithium reagents.[4,9] Recent work[10] on the mechanism of the reaction of LiH with CO is of special interest.

We recently reported[11] some new synthetic applications of the insertion reactions of CO into lithium dialkylamides previously communicated.[12] These reactions, usually used to produce alkylformamides,[13] can be employed in the synthesis of compounds with more than one carbonyl functionality, which would be difficult to prepare otherwise. The mechanism for product formation would suggest double carbonylation of the reagent: the high instability of the first intermediate proposed for this reaction precludes its isolation and an independent experimental determination of the subsequent steps. Some indirect experimental tests have been performed in order to suggest the mechanisms by which the different products are formed[11] and, therefore, a theoretical calculation of their feasibility may be useful. The geometries of some model reagents as well as those of the various intermediates were optimized and the energies of the different parallel and/or consecutive steps were calculated using semi-empirical all-valence electron SCF-MO methods.

Results and Discussion

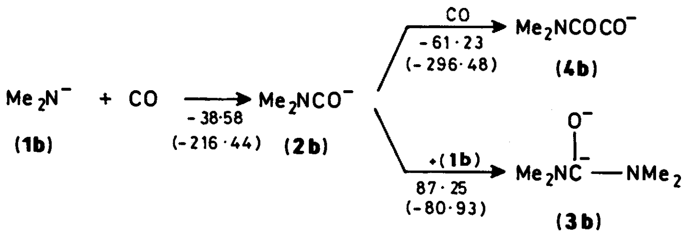
Theoretical Procedure.—The size of the molecules under study renders an *ab initio* MO analysis too expensive. Semiempirical INDO_1[4] and MNDO[15] procedures were examined and an IBM 370 computer was used for the calculations. Geometry optimization was performed in the first case using a GEOMO-INDO method and in the second with the MNDO program in conjunction with the Davidson–Fletcher–Powell procedure.[16] The three programs were obtained through *QCPE*[17] and adapted to run on the IBM 370 computer. The standard programs were modified to an extended basis of maximum 99 atomic orbitals. Except where noted otherwise, all geometrical variables were allowed to optimize.

Reagents and Intermediates.—The geometry of the lithium dimethylamide was calculated using the GEOMO-INDO procedure. The optimized geometry† shows a strong deformation from standard values: both methyl groups are moved closer to the lithium atom ($\mathrm{Li\widehat{N}C} = 79°$) which is thus partially co-ordinated to both carbon atoms. (A recent 'ab-initio' study of the geometry of α-lithiomethylamine[18] shows a planar triangular shape for the optimized geometry in which the lithium atom bridges the C–N bond whereas the lower energy acyclic isomeric form has $\mathrm{Li\widehat{N}C} = 76.5°$). Since it is highly unlikely that this would be the real structure of the reagent its dimer was also calculated starting from a geometry in which both lithium and nitrogen atoms are located on the vertices of a rhombus. The optimized geometry is now closer to the standard values: each lithium atom is mainly co-ordinated to both nitrogen atoms and to the other lithium and, to a lesser extent, to two carbon atoms. The smaller deformation and increased lithium co-ordination make the energy of the dimer smaller than that of the monomer by *ca.* 300 kcal $\mathrm{mol^{-1}}$. Although this figure is an overestimate and does not have absolute meaning it is of the right magnitude. It has been recently found[19] by *X*-ray diffraction that lithium bis(trimethylsilyl)amide etherate exists as a dimer with the nitrogen and lithium atoms located at the opposite vertices of a rhombus and the lithium atom trico-ordinated (to both nitrogen atoms and one oxygen atom).

To avoid the strong geometry deformation due to the lithium atom and since calculations of dimer structures would not be possible in all the cases, the following calculations were performed on the corresponding anions. Although the experi-

---

† For this and all other reagents and intermediates calculated in the present work, lists of all the bond lengths and angles are available on request.



Scheme 1.

mental determination used bulky *N*-substituents (such as butyl, pentyl, morpholyl, cyclohexyl, *etc.*), only methyl groups were used for the calculations in order to minimize computational requirements. The first intermediate proposed in the reaction, the anion, (**2b**) (see Scheme 1), shows a planar structure by both methods. The INDO calculation localizes almost the whole of the extra charge on the carbonyl carbon atom while the MNDO method delocalizes it between that atom, the oxygen atom, and the nitrogen atom giving a more carbene-like structure. Carbamoyl–actinide complexes are stable and they have been shown to exhibit carbene-like structures by spectroscopic and *X*-ray diffraction studies.[2b,20]

The anion (**4b**), exhibits peculiar behaviour. Starting from a

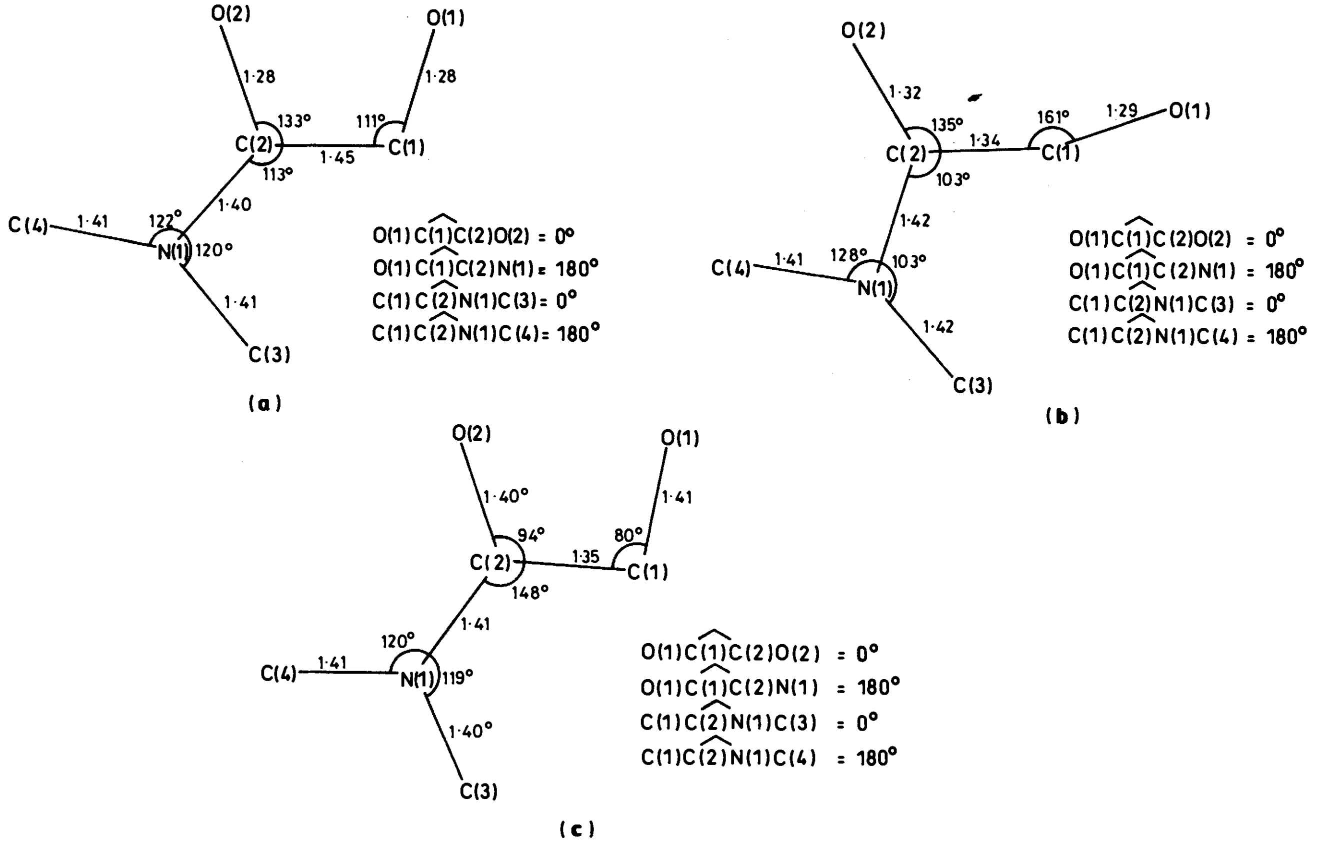


Figure 1. Bond lengths (Å), bond angles (°), and dihedral angles (°) calculated for anion (**4b**) by GEOMO-INDO method.

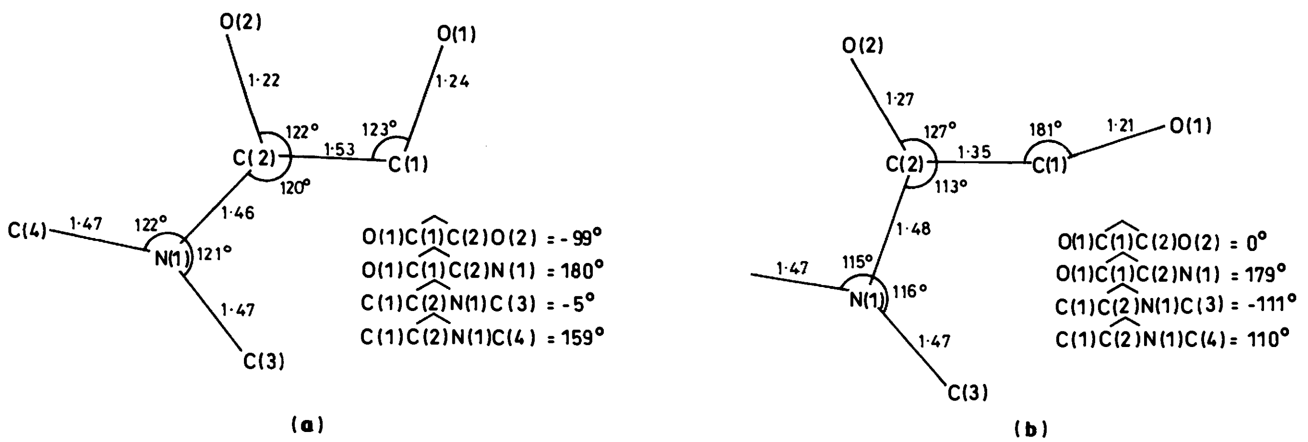


Figure 2. Bond lengths (Å), bond angles (°), and dihedral angles (°) calculated for anion (**4b**) by MNDO method.

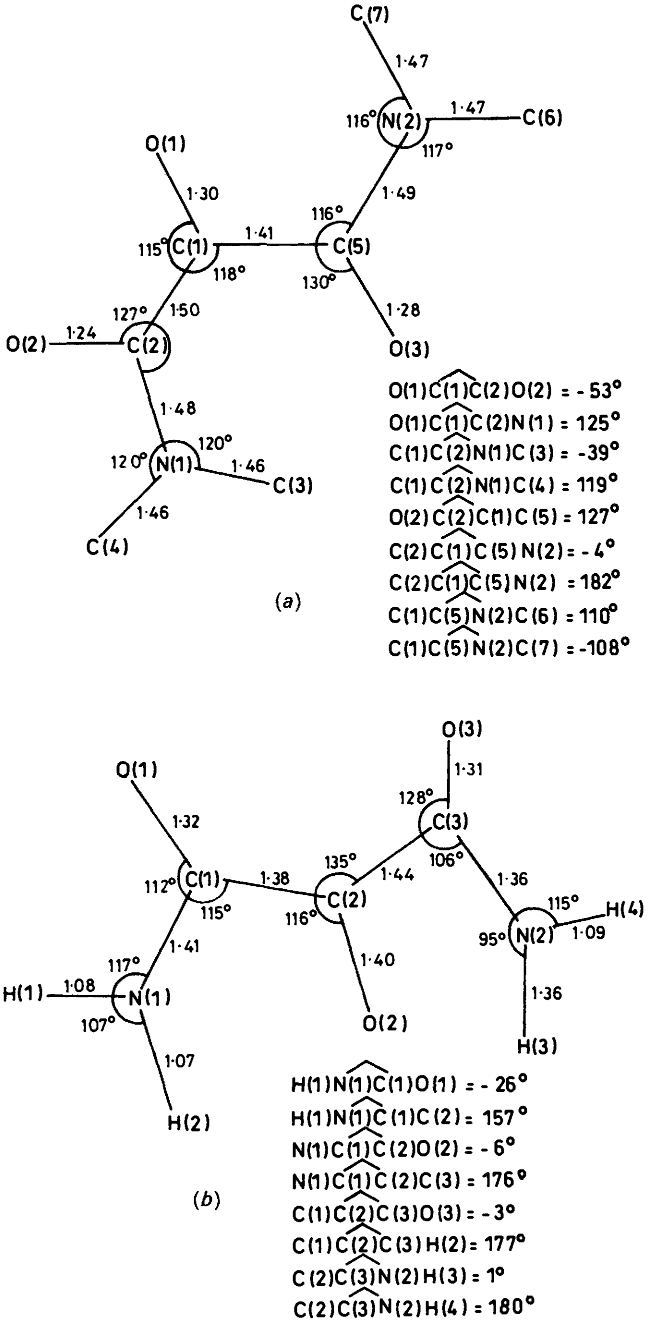


Figure 3. Bond lengths (Å), bond angles (°), and dihedral angles (°) calculated by: (*a*) MNDO for the dianion (**3b**) and (*b*) GEOMO-INDO for the dianion (**6a**).

Table 1. Heats of formation of amide and carbamoyl(oxo)methanide anions by the MNDO method.

Anion	ΔH_f°/kcal mol^{-1}
(**1b**)	17.08
(**2b**)	−21.62
(**3b**)	*a*
(**4b**)	−58.50
(**5b**)	45.19
(**6b**)	−11.10

[a] No convergence attained.

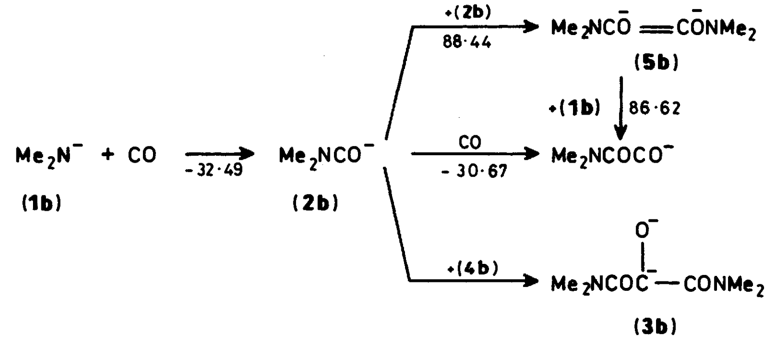
structure similar to that shown in Figure 1(*a*) the GEOMO-INDO optimization changes the standard bond lengths and angles slightly, and the structure is essentially planar (the calculated optimized parameters for this and other compounds are indicated in the Figures). Starting from Figure 1(*b*), an alternative optimized geometry very similar to the initial one (the main change is in $\widehat{CCO}$ = 161°) is obtained which is 45 kcal mol^{-1} more stable than Figure 1(*a*). Finally, a starting structure similar to Figure 1(*b*), but with the $\widehat{CCO}$ angle considerably smaller, produces an optimized geometry [Figure 1(*c*)] which is 90 kcal mol^{-1} more stable than Figure 1(*a*). In contrast, MNDO leads to optimized structures similar to Figure 1(*a*) [Figure 2(*a*)] and Figure 1(*b*) [Figure 2(*b*)] but Figure 2(*a*) is more stable than Figure 2(*c*). Figure 1(*c*) produces, by MNDO, the same optimized geometry as that obtained from Figure 1(*a*).

The MNDO geometry for intermediate (**6b**) (Scheme 2) is shown in Figure 3(*a*). The amino groups are out of plane and conjugation is only observed between the C(1)–C(5) double bond and the oxygen atoms attached to it. With primary amino groups the optimized structure given by GEOMO-INDO is shown in Figure 3(*b*): the structure is planar except for one amino group, and extended conjugation and strong intramolecular hydrogen bonding (H_3–O_2) is observed. Finally the intermediates (**5**), for which two structures (ene-diolate or keto-dianion) are conceivable give, regardless of the starting geometry and the method used, similar optimized geometries [INDO: Figure 4(*a*); MNDO: Figure 4(*b*)]. The double bond and the four substituents are almost coplanar and the nodal planes containing each nitrogen lone pair are almost perpendicular to the double-bond plane. This geometry is preferred regardless of whether the amino group is substituted by a methyl group. The rest of the intermediates calculated in the present work produce optimized structures which are very close to the standard starting geometries.

Heats of Formation of the Intermediates and Thermodynamic Scheme of Reactions.—It is known that INDO does not satisfactorily reproduce absolute energy values, therefore, Table 1 gathers together the heats of formation of the proposed intermediates which have been predicted only by the MNDO procedure. It has been previously found that MNDO gives satisfactory results for substituted oxomethanides.[9] It can be observed from Table 1 that most of the suggested carbonylation intermediates have favourable heats of formation.

To account for the formation of the two compounds recently reported[11,12] a double carbonylation of the reagent is suggested. This process has been found to be thermodynamically unfavourable[21,22] in the case of M–R substrates. Scheme 3 shows the energy changes involved in each step calculated by the MINDO [the MNDO calculation for intermediate (**3a**) does not converge] and the INDO (values in parentheses) methods. It can be observed that by both methods the double carbonylation is a thermodynamically favourable process. In contrast, formation of dianionic intermediates is not favoured by MINDO calculation.

To determine the influence of alkyl substituents, calculations on the dimethylamide reactions were then performed and the results are shown in Scheme 1. It can be observed that the presence of alkyl groups affects the heat of formation of (**2b**) and (**3b**) [compared with (**2a**) and (**3a**)] but has almost no effect on the formation of (**4b**) which is again thermodynamically favoured. Finally, since MNDO is more accurate than MINDO, MNDO calculations were performed for the production of all the intermediates that give energy convergence, the results are shown in Scheme 2 and it is again observed that double carbonylation is thermodynamically favoured.



Scheme 2.

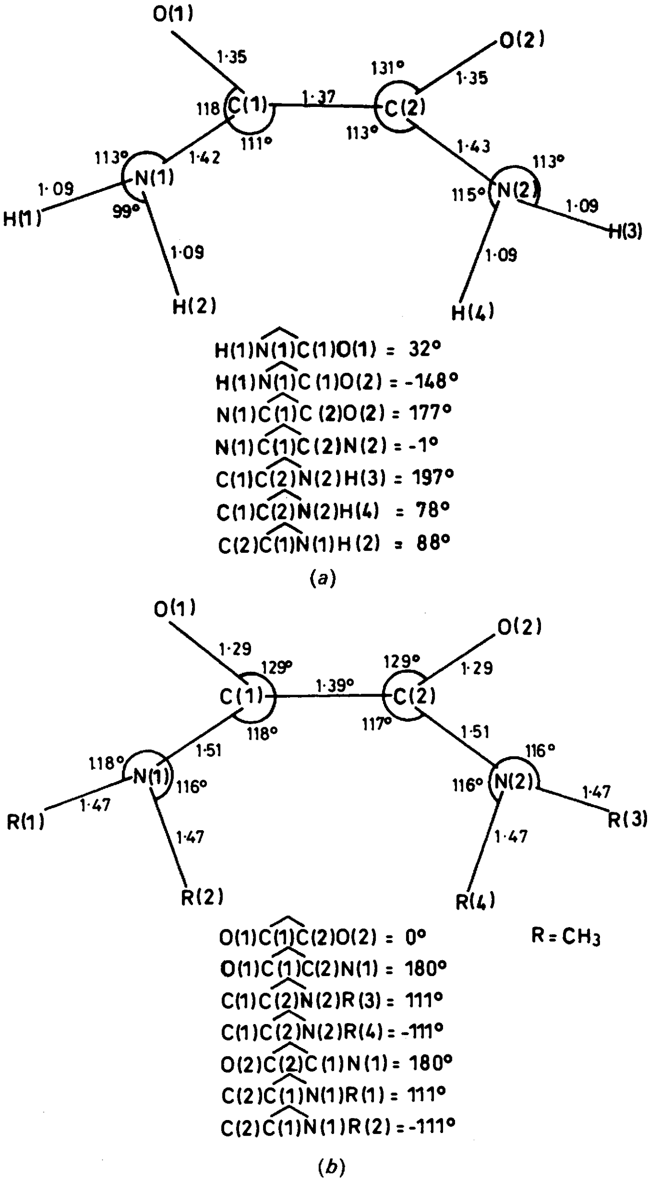


Figure 4. Bond lengths (Å), bond angles (°), and dihedral angles (°) calculated by: (*a*) INDO for dianion (**5a**) and (*b*) MNDO for dianion (**5b**).

Table 2. Calculated total energies (au) of neutral and anionic species in a medium of ε_r = 5. Method CNDOSOL.

Species	Energy	Species	Energy
CO	−23.96	(**1a**)	−13.03
NH_3	−13.38	(**2a**)	−37.99
H_2NCHO	−37.76	(**3a**)	−52.37
Me_2NH	−30.28	(**4a**)	−62.75
Me_2NCHO	−54.61	(**5a**)	−77.74
(**1b**)	−30.85	(**6a**)	−102.88
(**2b**)	−55.53	(**7**)	−52.11
(**3b**)	−88.76	(**8**)	−101.80
(**4b**)	−80.23		

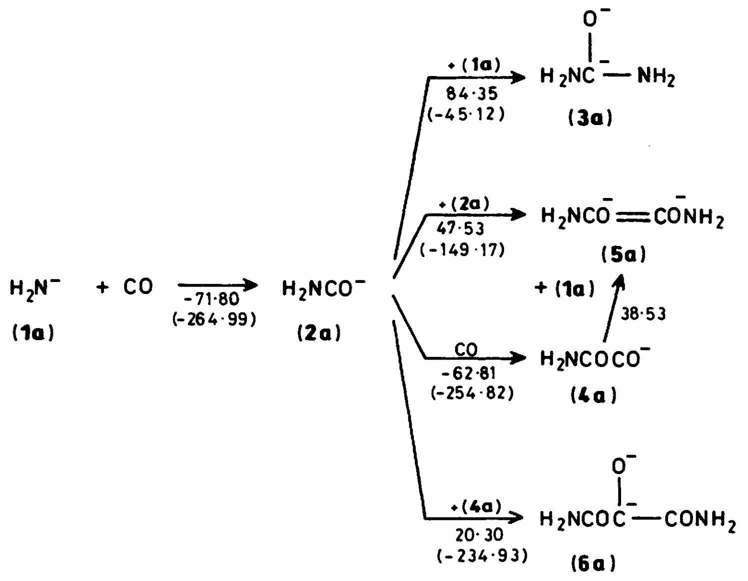
The above energy schemes are consistent with all the experimental results except one: they do not reproduce the relationship between the energies of activation of two alternative steps. In fact, it was found that decreasing temperatures favoured formation of dialkyl formamide as opposed to the bis(*N*,*N*-dialkylcarbamoyl)(oxido)methanide (the dialkylglyoxylamide is isolated as its hemi-hydrate). Although based on intermediates (and not on the real transition states) the present energetic schemes would suggest for the last reaction an energy of activation smaller than that for the first. It can be observed in Table 1 and in the Schemes that calculations excessively destabilize dianions. The same can be observed in some calculated acid-base equilibria in which the amide/ion-monoprotonated intermediate pairs are more stable than the amine/dianionic intermediate pairs. These results are not in accord with the results found in those cases in which it has been possible to determine the equilibrium position.[23]

The overestimation in the energy of the dianionic intermediates is due to the high instability expected *in vacuo* for compounds carrying two close negative charges; this could be partially solved by considering the interaction with solvent molecules. A simple treatment developed by Klopman[24] can be applied to this problem, although one drawback is that solvent interactions are considered on the basis of MOs calculated *in vacuo*. To improve this method the solvent interaction terms were introduced into the Hamiltonian of an SCF-CNINDO 3.3.3 producing method CNDOSOL.[25] Calculations were performed for several values of the relative permittivity* in the range 1–50. The input geometries were those given by the GEOMO-INDO procedure.

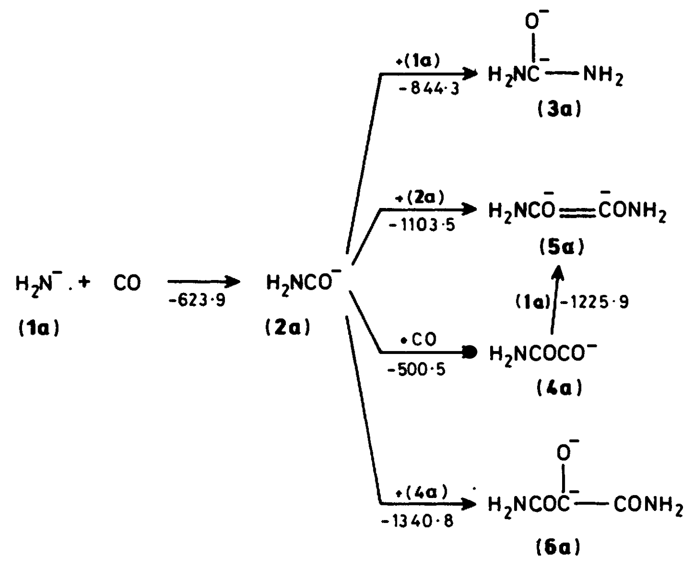
The results obtained from a consideration of solvent effects, even at this elementary level, are very significant. Table 2 shows the energies given by CNDOSOL for a value of ε_r = 5 (ε_r for ethyl ether = 4.3). Although the values have no absolute meaning they show the extra stabilization of the dianionic species afforded by solvent interaction. Schemes 4 and 5 show the effects of solvent on the reactions of amide and dimethylamide, respectively, in a medium of ε_r = 5. Comparing

---

* Formerly dielectric constant.



Scheme 3.



Scheme 4.

the data in Scheme 4 with those in parentheses in Scheme 3 the stabilizing effect of the solvent is noticeable, especially as regards the dianionic intermediates. The same reasoning can be applied to Scheme 5 when these data are compared with those of Scheme 1. Furthermore, formation of the double carbonylation intermediates (**4**) (which will produce dialkylglyoxylamide hemi-hydrate upon work-up), would have a higher energy of activation than that for formation of the dianionic intermediates (**3**) (which will produce dialkyl formamide); this is in fact found experimentally.[11,12]

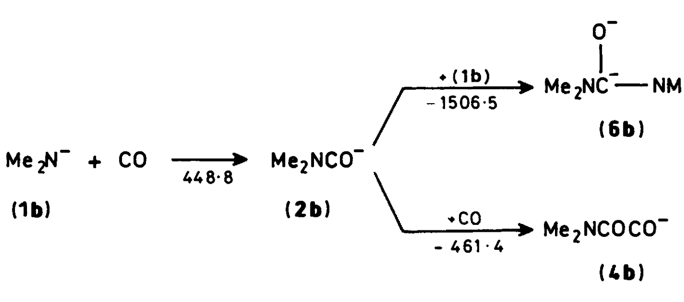
Finally, the energy changes involved in various equilibria were also calculated and the results are shown in equations (1)–(3). The equilibrium positions are consistent with what is

$$H_2NCHO + \mathbf{(1a)} \xrightarrow{-362.8} \mathbf{(2a)} + NH_3 \qquad (1)$$

$$\mathbf{(7a)} + \mathbf{(1a)} \xrightarrow{-383.5} \mathbf{(3a)} + NH_3 \qquad (2)$$

$$\mathbf{(8a)} + \mathbf{(1a)} \xrightarrow{-898.9} \mathbf{(6a)} + NH_3 \qquad (3)$$

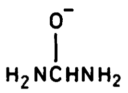
expected on the basis of the acid-base properties of some of the compounds involved. Unfortunately, data on the pK_a of the intermediates are not experimentally available. The relative values obtained by calculation can be used to estimate the effect that the presence of proton donors should have on the course of the reaction. In fact, taking into account the data of Table 2 and those of the present proton transfers, it can be observed that protonation of the intermediate (**6a**), leading to tartronamide, is a much more difficult process than protonation of the other intermediates. This could explain the spectacular effect observed on addition of the free amine, leading to the production of glyoxylamides in high yields,[11] and it provides further insight into the mechanisms of the different reactions involved.



Scheme 5.

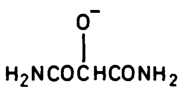
Conclusions

The present work offers calculations on the geometries and energies of the various intermediates involved in CO insertion



$H_2N\overset{\overset{O^-}{|}}{C}HNH_2$

(7a)



$H_2NCO\overset{\overset{O^-}{|}}{C}HCONH_2$

(8a)

into Li–N bonds in lithium dialkylamides. The results are consistent with the proposed intermediates and they show that the processes are thermodynamically favourable. Although the energies for the various alternative pathways likely to occur after the first intermediate was formed [the dimethylamino(oxo)methanide anion] do not follow the trend that would be expected on the basis of the observed temperature effect on product composition, this trend is predicted to be of the correct magnitude if considerations of solvent interactions are added. The equilibrium positions for several of the acid-base equilibria involved are also estimated and they can account for the effects observed on addition of free amine.

Acknowledgements

The authors are indebted to the National Research Council of Argentina (CONICET) for financial support. Calculations were performed through the courtesy of IBM Buenos Aires which is deeply acknowledged.

References

1 Part 5, N. S. Nudelman and P. MacCormack, *J. Chem. Soc., Perkin Trans. 2*, 1987, 227.

2 (*a*) S. L. Webb, C. M. Giandomenico, and J. Halpern, *J. Am. Chem. Soc.*, 1986, **108**, 345; (*b*) K. G. Moloy, P. J. Fagan, J. M. Manriquez, and T. Marks, *J. Am. Chem. Soc.*, 1986, **108**, 56; (*c*) D. J. Darensbourg, R. K. Hanckel, C. G. Bauch, M. Pala, D. Simmons, and J. N. White, *ibid.*, 1985, **107**, 7463.

3 N. Koga and K. Morokuma, *J. Am. Chem. Soc.*, 1986, **108**, 6136; 1985, **107**, 7230.

4 P. R. Schleyer, T. Clark, A. J. Kos, G. W. Spitznagel, C. Rohde, D. Arad, K. N. Houk, and N. G. Rondan, *J. Am. Chem. Soc.*, 1984, **106**, 6467.

5 D. Seyferth, R. M. Weinstein, W. Wang, R. C. Hui, and C. M. Archer, *Isr. J. Chem.*, 1984, **24**, 167.

6 C. Narayana and M. Periasamy, *Synthesis*, 1985, 253.

7 (*a*) A. A. Vitale, F. Doctorovich, and N. S. Nudelman, *J. Organomet. Chem.*, 1987, **332**, 9; (*b*) N. S. Nudelman and A. A. Vitale, *J. Org. Chem.*, 1981, **46**, 4625.

8 J. Chandrasekhar, J. G. Andrade, and P. R. Schleyer, *J. Am. Chem. Soc.*, 1981, **103**, 5612.

9 J. Kaneti, P. R. Schleyer, T. Clark, A. J. Kos, G. W. Spitznagel, J. G. Andrade, and J. B. Moffat, *J. Am. Chem. Soc.*, 1986, **108**, 1481.

10 E. Kaufmann, P. R. Schleyer, S. Gronert, A. Streitwieser, and M. Halpern, *J. Am. Chem. Soc.*, 1987, **109**, 2553. (We thank Prof. P. R. Schleyer for a pre-print of this paper.)

11 N. S. Nudelman and D. G. Perez, *J. Org. Chem.*, 1988, **52**, 408.

12 N. S. Nudelman and D. G. Perez, *J. Org. Chem.*, 1983, **48**, 133.

13 (*a*) V. Rautenstrauch and F. Delay, *Angew. Chem., Int. Ed. Engl.*, 1980, **19**, 726; (*b*) V. Rautenstrauch and M. Joyeux, *ibid.*, 1979, **18**, 83.

14 J. A. Pople and D. L. Beveridge, 'Approximate Molecular Orbital Theory,' McGraw-Hill, New York, 1970.

15 M. J. S. Dewar and W. Thiel, *J. Am. Chem. Soc.*, 1977, **99**, 4899.

16 (*a*) W. C. Davidon, *Comput. J.*, 1968, **10**, 406; (*b*) R. Fletcher and M. J. D. Powell, *ibid.*, 1963, **6**, 163.

17 Quantum Chemistry Program Exchange, Indiana University; Bloomington, Indiana, U.S.A.

18 T. Clark and P. R. Schleyer, *J. Chem. Soc., Chem. Commun.*, 1981, 579.

19 M. F. Lappert, M. J. Slade, A. Singh, J. L. Atwood, R. D. Rogers, and R. Shakir, *J. Am. Chem. Soc.*, 1983, **105**, 302.

20 P. J. Fagan, J. M. Manriquez, S. H. Vollmer, C. S. Day, and T. J. Marks, *J. Am. Chem. Soc.*, 1981, **103**, 2206.

21 F. Ozawa, T. Sagimoto, Y. Yuasa, M. Santra, T. Yamamoto, and A. Yamamoto, *Organometallics*, 1984, **3**, 683; F. Ozawa, T. Sagimoto, Y. Yamamoto, and A. Yamamoto, *ibid.*, 1984, **3**, 692.

22 A. Sen and J.-T. Chen, *J. Am. Chem. Soc.*, 1984, **106**, 1506.

23 A. S. Fletcher, K. Smith, and K. Swaminathan, *J. Chem. Soc., Perkin Trans. 2*, 1977, 1881.

24 G. Klopman, *Chem. Phys. Lett.*, 1967, **1**, 200.

25 F. C. Facelli, C. G. Giribet, and R. H. Contreras, *Int. J. Quantum Chem.*, 1984, **25**, 515.

Received 12*th January* 1988; *Paper* 8/00115D