

## STEREOCHEMISTRY OF DISSOLVING METAL REDUCTION OF KETONES

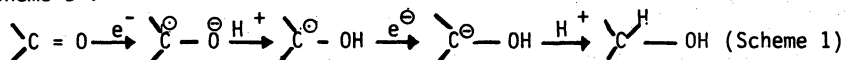
André RASSAT

Université Scientifique et Médicale de Grenoble, E.R.A. n° 20, Laboratoire de Chimie Organique Physique du Département de Recherche Fondamentale du C.E.N.G., 85, F. 38041 GRENOBLE CEDEX.

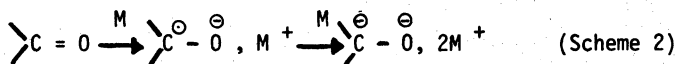
Abstract - Experimental results on the reduction of ketones by metals in liquid ammonia are summarized. The product yields are very dependent upon the choice of experimental conditions. Theoretical results are presented on some intermediate or products involved in these reductions. Ketyl radical-anions are non planar in their equilibrium conformation. Protonation on oxygen is favoured. The composition of equilibrium mixture of epimers can be calculated to a good approximation.

The reduction of ketones by dissolving metals and the related electrochemical reductions have been much studied. House (1) has summarized the recent work. The main features of these reactions are relatively well understood. The first step is the formation of a ketyl, and the ratio of the two epimeric alcohols obtained is not necessarily the equilibrium ratio. However, it is still impossible to make quantitative prediction on the steric course of these reactions. In this talk, I would like to present some experimental results which show the complexity of the reactions and theoretical treatments of two related problems: the structure of the ketyl radical-ion and the stability of epimeric alcohols.

The most common dissolving-metal reduction is probably the sodium-and-alcohol reaction (1), an heterogeneous reaction. We preferred to study the homogeneous reaction in liquid ammonia (2-12). Other workers (e.g. 13-17 and ref. therein) have also studied this reaction. Every component of the reaction mixture, the solvent (liquid ammonia), the ketone to be reduced, the electron donor (the metal) and a proton donor are necessary, as may be seen in reaction scheme 1 :



A co-solvent may be used if the ketone is not soluble in liquid ammonia. Various procedures may be found in the literature (1), the ketone, the metal and the proton donor being added in different order to the liquid ammonia. We have chosen two extreme types A and B : A) The ketone and proton donors (ethanol under standard conditions) are dissolved in liquid ammonia and the metal is added to this solution. The rate of reduction is apparently controlled by the metal dissolution. B) The metal is first dissolved in liquid ammonia, care being taken that no proton donor be present at this stage. The ketone is added to the blue solution. After 30 minutes, a proton donor (ethanol under standard conditions) is added before work-up. It is hoped that in case A all the steps of scheme 1 can occur, while in case B protonation is forbidden and scheme 2 is now to be considered before protonation.



(in this scheme 2, ionic structures are given, but different ion-pairs of various degrees of aggregation are possible (1) ). Other procedures may be considered as intermediate : for instance, adding the metal to the ketone in liquid ammonia may be a type A reaction at the beginning, if some water is present in liquid ammonia, and then type B, when the proton donor is added after the A type reaction is over.

The experimental results can be summarized in the following way : In monocyclic cyclohexanone derivatives (15), A-type reduction gives the more stable equatorial epimer in a larger than 9:1 ratio to the less stable epimer. In polycyclic ketones, various ratios of stable to unstable epimer have been found (1-24). In some cases (3-9, 13-18, 23), pinacols are formed, sometimes in 90% yield. (It may be noted that a symmetrical ketone gives one alcohol and one pinacol only, a prochiral ketone gives one racemic alcohol and two different pinacols (meso and *dℓ*), an optically active ketone gives two epimeric alcohols ( $\alpha$  and  $\beta$ ) and three different pinacols ( $\alpha\alpha$ ,  $\alpha\beta$  and  $\beta\beta$ ) while the corresponding racemic ketone may give two racemic epimeric alcohols and six different pinacols (racemic- and meso- ,  $\alpha\alpha$ ,  $\alpha\beta$  and  $\beta\beta$ ). Two different pinacols have been obtained from d-camphor 1 (3, 17) and from A-nor-cholestan-2-one 2 (4), but it is difficult to determine their stereochemistry. A series of pinacols has been obtained from norcamphor 3 (8, 9, 11, 15) ).

These experimental data (yields of pinacols and of alcohols, and ratio of the two epimeric alcohols) may sometimes strongly depend upon the experimental conditions and on the nature of the metal used. Since some contradictory results have appeared in the literature, I would like to illustrate this dependence :

a) Cases have been found where the products are insensitive to the reaction conditions : For fenchone 4, reduction gives no pinacol and less than 5% exo epimer and more than 95% endo epimer (6), whatever the metal or the type of reaction. The equilibrium mixture is probably 30% exo - 70% endo (6).

b) The ratio of epimers may be insensitive to the reaction conditions but the relative yields of pinacols and of alcohols change : In androstan-17 one 5, less than 5% androstan-17 $\alpha$ -o1 is obtained (in the  $\alpha$  +  $\beta$  alcohol mixture) (the equilibrium mixture is 35% $\alpha$ , 65%  $\beta$ ) but the yield of pinacol (Table I) varies between 35% and 2% depending upon the metal used and the type of reduction (11, 12).

TABLE I

	Cs	K	Na	Li	Ba	Sr	Ca
A type		13	34	6			
B type	3	6	17	28	10	12	0

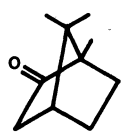
Yield of pinacols obtained in the reductions of androstan-17 one

Similar results have been obtained for  $\alpha$ -fenchocamphorone 6, 1-methyl norcamphor 7, the most abundant epimer being the most stable for 6 and the less stable for 7.

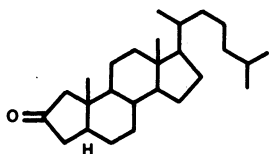
c) The ratio of epimers and the pinacols-yield vary with the metal used and do not vary much with the type of reduction : This is the case for A-norcholestan-2-one 2 (4) ; Table II gives the percentage (*r*) of  $\alpha$ -epimer obtained in the alcohols mixture, and the pinacols yield (*y*) :

TABLE II

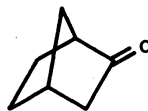
		K	Na	Li
A type	<i>r</i>	14	33	33
	<i>y</i>	55	52	41
B type	<i>r</i>	20	33	43
	<i>y</i>	47	32	27



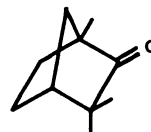
1



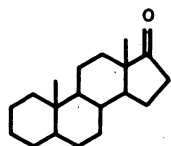
2



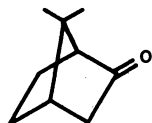
3



4



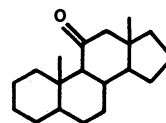
5



6



7



8



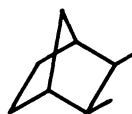
9



10



11



12



13



14



15



16



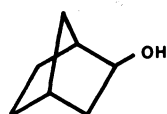
17



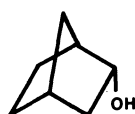
18



19



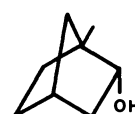
20



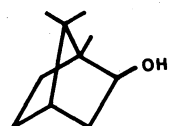
21



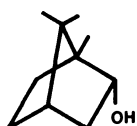
22



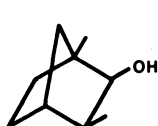
23



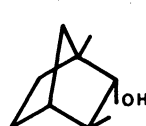
24



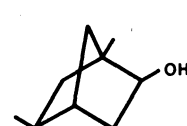
25



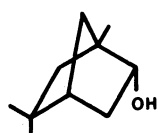
26



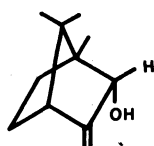
27



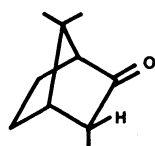
28



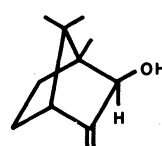
29



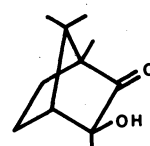
30



31



32



33

d) The ratio of epimers does not change much with different metals but changes drastically with the type of reduction : This is the case of androstan-11 one 8 (5, 12) for which table III gives the % of epimer in the alcohol mixture.

TABLE III

	Cs	K	Na	Li	Ba	Sr	Ca
A type		5	6	4			7
B type	42	42	42	43	35	42	21

The  $\alpha$  epimer is probably the most stable (5,12).

e) It is now possible to discuss some conflicting results in the literature : Reduction of norcamphor 3 has been studied by A. COULOMBEAU (8-11) in our group and by J.W. HUFFMANN and J.T. CHARLES (15) :

Table IV gives the yield of pinacols obtained under standard conditions in A-type or B-type reductions a) by our group, b) by HUFFMANN and CHARLES.

TABLE IV

	N(Et) <sub>4</sub> <sup>*</sup>	Cs	Rb	K	Na	Li	Ba	Sr	Ca
A	a			12		15			
	b		0	0	0	0			
B	a	0	48	54	57	61	53	38	34
	b			0	0	0	28		

\* In this reduction, the metal (barium) has been precipitated by N(Et)<sub>4</sub>Cl

These discrepancies are difficult to explain. However, in our hand, the recovery of material was quantitative, while HUFFMANN and CHARLES results account for less than 50% of the material. We may also notice that in our hands, the pinacol yield varies between 25 and 100%, in the B-type reduction with lithium (8-11). The discrepancies are less for the percentage of epimer : Table V gives the % of exo alcohol in the alcohols mixture.

TABLE V

	N(Et) <sub>4</sub> <sup>*</sup>	Cs	Rb	K	Na	Li	Ba	Sr	Ca
A	a			11		19			
	b		9	10	15	15			
B	a	10	17	17	22	30	30	30	25
	b		9	20	29	27			

\* In this reduction, the metal (barium) has been precipitated by N(Et)<sub>4</sub>Cl

The case of camphor is important : We had first noticed that a) the alcohol mixture obtained by the dissolving metal reductions was different from the equilibrium mixture (2); b) In liquid ammonia, the ratio of epimer obtained (2) and the pinacol yield (3) changed drastically with the conditions and the metal used. This was confirmed in a detailed study (7-11) by A. COULOMBEAU. At the same time, HUFFMANN and CHARLES (15) could not reproduce some of our results. However, this point was studied later by MURPHY and SULLIVAN (17) who confirmed our previous results :

TABLE VI

	$N(ET)_4^*$	Cs	Rb	K	Na	Li	Ba	Sr	Ca
A	a			0	0	28	0		0
	b								
	c			0	0	0			
B	a	0	0	0	20	60	0		0
	b		0	0	20	70	0	0	0
	c			0	0	17			

\* see Table IV

Table VI gives the pinacols yield obtained under standard conditions A and B by : a) our group, b) MURPHY and SULLIVAN, c) HUFFMANN and CHARLES, in the reductions of camphor.

TABLE VII

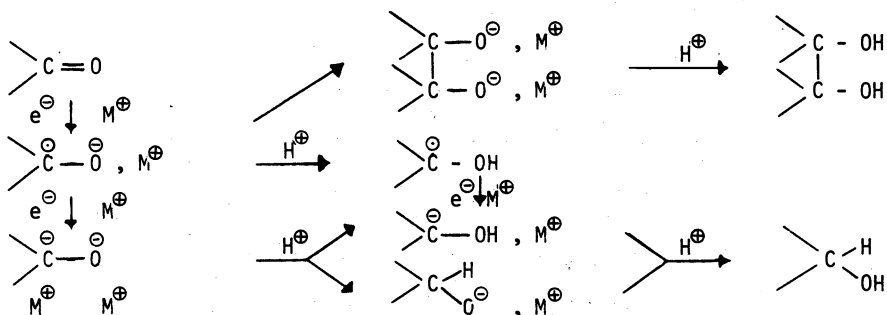
	$N(ET)_4^*$	Cs	Rb	K	Na	Li	Ba	Sr	Ca
A	a			42	23	15	30		20
	b								
	c			13	13	11			
B	a	39	82	77	60	42	23	32	28
	b		78		58	40	20	29	30
	c				22	19	16		

\* see Table IV

Table VII gives the % exo epimer in the alcohol mixture found by : a) our group, b) MURPHY and SULLIVAN, c) HUFFMANN and CHARLES, under standard conditions A and B.

It is apparent that under standard conditions, the reductions in liquid ammonia give reproducible results. Although the origin of the reported discrepancies may be trivial, one may speculate that some more subtle influences such as differences in magnetic field (25) play a role.

The experimental data on these reductions are thus mainly yields and isomer ratio. From these data, various mechanisms have been proposed (1, 3, 10, 11, 15, 17). It is generally accepted that products formation is kinetically controlled and that some of the steps of scheme 3 are involved. However, no quantitative data can be given on the relative rates of the different processes, on the reversible nature of some steps, on the structure of the ion pairs involved, and on their degree of aggregation. Detailed kinetic and physico-chemical studies of all the intermediates and all the steps are probably beyond our present capacities (See also ( 26 ) for a detailed study of the reduction of  $\alpha$ -diketones.)



We have chosen to study two problems : the *structure of the ketyl radical-ion* formed in the first step, since its conformation may have some implication on the stereochemistry of the products, and the difference of *stability of the epimeric alcohols* formed in the last step.

#### The structure of ketyl radicals :

Drs. J. DOUADY, Y. ELLINGER and R. SUBRA, from this laboratory, in collaboration with Dr. G. BERTHIER, have studied the simple ketyl  $\text{H}_2\text{CO}^-$  (For references to previous work, see (27)). Its equilibrium geometry has been studied by energy minimisation as a function of distances and angles,  $\alpha$  being the out-of-plane angle between CO and  $\text{H}_2\text{C}$  plane. Two methods have been used :

*A perturbation method, (to 3rd order) with Configuration Interaction using Localized Orbitals (PCILO), in the semi-empirical CNDO approximation. The original PCILO method (28) has been modified (29, 30) for open-shell molecules and in order to take into account the CO three-electrons bond.*

*An ab-initio method, the spin-restricted LCAO-SCF method of Roothaan with some Configuration Interaction (27). Two basis of Gaussian-type orbitals were used : Basis I : (7s, 3p/3s) contracted to (3s, 2p/1s) ; Basis II was basis I plus polarization functions (3s, 2p, 1d/1s, 1p).*

Table VIII gives the optimized geometry for  $\text{H}_2\text{CO}^-$  in its equilibrium conformation and the barrier to inversion, calculated as difference between the energy for  $\alpha = 0$  and  $\alpha$  at equilibrium.

TABLE VIII : Calculated equilibrium conformational barrier to inversion using PCILO (a), and ab initio SCF method with basis I (b) or II (c).

<u>Geometrical parameters</u>	<u>PCILO (a)</u>	<u>SCF I (b)</u>	<u>SCF II (c)</u>
CO (Å)	1.33	1.33	1.30
CH (")	1.13	1.03	1.09
HCH (°)	114	117.5	116.5
$\alpha$ (°)	30	24	27
Barrier to inversion, kcal/mole	1.63	0.446	0.875

The CO bond is significantly longer than in  $\text{H}_2\text{CO}$  (31). As usual, the CNDO parameterisation gives too large a barrier. The 0.875 kcal/mole barrier is probably a better estimate. In  $\text{H}_2\text{NO}$ , the inversion barrier has been calculated (27) to be smaller (0.064 kcal/mole) and the stable conformation of stable nitroxides is found by diffraction methods to be planar for symmetrical and bent for non symmetrical molecules (32). By comparison, it is concluded that ketone radical-ions are bent, the out of plane angle being ca  $30^\circ$  and the inversion barrier slightly less than 1 kcal/mole. If this is correct, the stereochemistry of the reduction may be discussed in term of a bent radical-ion (1, 10, 17).

The protonation step in the reduction may also be considered : What is the more favored process in ketyls, protonation at O or at C ? Although this may strongly depend upon solvation and/or complexation by the counter ion, we have tried to answer this question for a free ketyl : Using the electrostatic potential technique (33) it is possible, from the SCF wave function, to draw the  $\text{H}_2\text{CO}^-$  electrostatic potential (34). Since the species is negatively charged, the potential is attractive for a proton and rather spherical at large distances. It is more attractive around oxygen (ca -200 kcal/mole), than around C (ca -100 kcal/mole). A minimum (-249 kcal/mole) is found at the expected direction of an oxygen lone pair, at ca 1 Å from O. What is the meaning of this result ? The electrostatic potential approach gives only the first term of the interaction energy between  $\text{H}_2\text{CO}^-$  and  $\text{H}^+$ , in a perturbation development.  $\text{H}_2\text{COH}^\cdot$  has been calculated (35) and found to have a stable geometry corresponding to the minimum of the electrostatic potential of  $\text{H}_2\text{CO}^-$ . We believe that the protonation of  $\text{H}_2\text{CO}^-$  occurs at oxygen first (as expected from simple electronegativity consideration). This step is probably reversible, while protonation at carbon, if any, is probably irreversible and may be a step controlling the stereochemistry of products. Further discussion seems still more speculative.

We shall now turn to the study of relative stability of the reduction products. It was originally thought that dissolving metal reactions give the equilibrium mixture of alcohols (1). This is not the case, and the reaction is kinetically controlled. However, we have studied the stability of these alcohols. Experimentally, we have used acetone-isopropyl alcohol-potassium to equilibrate the potassium alcoholates (4, 6, 8). Some results are reported in Table X. In order to investigate all the reduction steps, it may be necessary to know the relative stability of unstable epimeric species (radicals or anions). Such an experimental determination may be impossible and calculation may be necessary. In order to test the methods, we have tried to calculate the relative stability of epimeric alcohols, for which experimental data were available. It is possible to measure the composition of an equilibrium mixture at different temperature T and to obtain the free energy difference  $\Delta G^\circ$  between isomers, from which the enthalpy and entropy differences  $\Delta H^\circ$  and  $\Delta S^\circ$  are calculated. These values are related to the experimental conditions and take solvation into account. In order to calculate these values, it is reasonable to identify the enthalpy of formation  $\Delta H$  to the energy of formation calculated for one molecule. However, the calculation is done for an isolated molecule and solvation cannot be explicitly taken into account.

In order to calculate the energy of formation, it is necessary to start from the geometry of minimal energy. Because quantum methods are too expensive for a complete optimisation, we have calculated this geometry by a standard molecular mechanics program. The initial geometries were taken from photographic projections of molecular models (36) and the minimisation of energy was searched by a simplex method (37). Using this optimised geometry, the energy of formation for each isomer was calculated (38) using PCILO method (28) in the CNDO approximation, for each isomer, thus giving the enthalpy differences. These differences

are not equal to those calculated using a non-optimized geometry (39, 40). The entropy differences between isomers were estimated (41) as arising mainly from entropy of rotation and entropy of mixing (42). The first term is a symmetry term, the second depends on the possibility of different conformers. These conformers were estimated (38, 41) by changing one or two torsional angles in the optimized molecule, calculating the energy as a function of this internal coordinate to find conformers secondary minima. Their relative proportion  $x_i$  is then estimated assuming a Boltzmann distribution, and the entropy of mixing is calculated as  $RT \sum_i x_i \log x_i$ . Having  $\Delta H^\circ$  and  $\Delta S^\circ$ , the  $\Delta G^\circ$  can be calculated, as well as the relative percentages of isomers at different temperatures. This procedure has been applied to three groups of bicyclo-[2,2,1] heptane derivatives. Hydrocarbons (38), alcohols (38-41) and ketols (41) : Monomethyl and dimethyl hydrocarbons have been equilibrated by other workers (43). The calculated and experimental values are given in Table IX.

TABLE IX : Calculated and experimental energy values and % at equilibrium for bicycloheptane hydrocarbon derivatives. (a) ref. (43).

Compounds		$\Delta G^\circ$ kcal/mole			
		calc.	exp.(a)	% calc.	% exp (a)
Methylnorbornane at 300°C	<u>9</u>	0	0	63.3	68
	<u>10</u>	0.62 $\pm$ 0.30	+0.89 $\pm$ 0.05	36.7	32
Dimethyl- norbornane at 160°C	<u>11</u>	0	0	83.6	91
	<u>12</u>	1.71 $\pm$ 0.30	2.28 $\pm$ 0.06	11.4	7
	<u>13</u>	2.43 $\pm$ 0.30	3.3 $\pm$ 0.3	5	2
	<u>14</u>	0	0	53.8	58.1
Dimethyl- norbornanes at 25°C	<u>15</u>	0.72 $\pm$ 0.30	0.78 $\pm$ 0.04	15.8	15.4
	<u>16</u>	0.98 $\pm$ 0.30	1.02 $\pm$ 0.05	10.2	10.4
	<u>17</u>	1.26 $\pm$ 0.30	1.38 $\pm$ 0.08	6.4	5.6
	<u>18</u>	1.09 $\pm$ 0.30	1.42 $\pm$ 0.08	8.5	5.3
	<u>19</u>	1.39 $\pm$ 0.30	1.43 $\pm$ 0.08	5.3	5.2

Table X gives our experimental and calculated results for bicyclic alcohols. The role of the optimized geometry is shown by including results obtained without optimisation (40). Table XI gives the results for 4 epimeric ketols 30, 31, 32, 33, without optimisation of geometry (41).

TABLE X : Calculated and experimental  $\Delta G^\circ$  for epimeric bicycloheptanol derivatives : a) non-optimized geometry (40), b) Optimized geometry (38), c) experimental values, d) ref.44, e) ref.45.

Compounds. (X=exo, N=endo)		$\Delta G^\circ$ calc.	$\Delta G^\circ$ calc.	$\Delta G^\circ$ Equilibration at 25°C (c)	$\Delta G^\circ$ calc.	$\Delta G^\circ$ calc.	$\Delta G^\circ$ Equilibration at 170°C (c)
		at 25°C (a)	at 25°C (b)		at 170°C (a)	at 170°C (b)	
Norbornéol X	20	1.28	0.46	-1.10	1.33	0.37	-0.97
Norborneol N	21						
Me-1 Norborneol X	22	1.19	-0.45		1.40	-0.26	-0.36
Me-1 Norborneol N	23						
Isoborneol X	24	0.72	0.62	0.73	0.84	0.73	0.61
Borneol N	25						
$\beta$ -Fenchol X	26	0.67	0.86		0.67	0.94	0.81
$\alpha$ -Fenchol N	27						
$\alpha$ -Isufenchol X	28	0.96	0.84		1.12	0.96	(d)(e)
$\beta$ -Isufenchol N	29						



TABLE XI : Calculated and experimental energy and entropy differences for the equilibrium between ketols 30, 31, 32, 33.

Isomer		<u>30</u>	<u>31</u>	<u>32</u>	<u>33</u>
$\Delta H^\circ$ (kcal/mole)	exp.	0	+0.48	+1.44	+2.24
	calc.	0	+0.84	+1.81	+2.02
$\Delta S^\circ$ (u.e.)	exp.	0	-0.5	+0.6	+0.8
	calc.	0	-0.22	+0.24	+0.29
$\Delta G^\circ$ (kcal/mole) at 65°	exp.	0	+0.66	+1.24	+2.0
	calc.	0	+0.91	+1.73	+1.93
$\Delta G^\circ$ (kcal/mole) at 100°	exp.	0	+0.68	+1.23	+1.98
	calc.	0	+0.92	+1.72	+1.92
$\Delta G^\circ$ (kcal/mole) at 165°	exp.	0	+0.70	+1.17	+1.93
	calc.	0	+0.93	+1.70	+1.89

The following conclusions can be drawn : The experimental results are very well reproduced for hydrocarbons, hindered alcohols and ketols. [These last molecules are hindered and also show internal hydrogen bonding (26)]. Discrepancies are noticed specially for norborneols 20 21, the least hindered alcohols. It is possible that the method we have used is satisfactory when solvation is negligible and that inclusion of solvation may give a fully satisfactory way to calculate the equilibrium ratios in isomeric mixtures.

*Acknowledgements* : The results discussed here have been obtained over a large period of time; My own interest in the area was started by Prof. G. OURISSON during my Doctoral thesis. A.M. GIROUD, and A. COULOMBEAU studied the dissolving metal reductions. J. DOUADY, Y. ELLINGER and R. SUBRA, in collaboration with G. BERTHIER, E. SCROCCO and J. TOMASI studied  $H_2CO^-$ . Y. BRUNEL (in collaboration with D. GAGNAIRE and H. FAUCHER) did the molecular mechanics work, and with C. COULOMBEAU, calculated the equilibrium ratio of epimers. I am deeply indebted to all of them and it is my pleasure to thank them here.

#### References

- (1) H.O. HOUSE, Modern Synthetic Reactions, 2nd edition, Benjamin, 1972, p. 145.
- (2) G. OURISSON and A. RASSAT, Tetrahedron Letters, 1960, 16.
- (3) A. RASSAT, Thesis, Paris, 1961 ; CNRS A 3721 n° 4572.
- (4) J.C. ESPIE, A.M. GIROUD and A. RASSAT, Bull. Soc. Chim. Fr., 1967, 809.
- (5) A.M. GIROUD, Thesis, Grenoble, 1967, CNRS A.O. 1666.
- (6) A. COULOMBEAU and A. RASSAT, Bull. Soc. Chim. Fr., 1965, 3338.
- (7) A. COULOMBEAU and A. RASSAT, Chem. Comm., 1968, 1587.
- (8) A. COULOMBEAU and A. RASSAT, Bull. Soc. Chim. Fr., 1970, 4393.
- (9) A. COULOMBEAU and A. RASSAT, Bull. Soc. Chim. Fr., 1970, 4399.
- (10) A. COULOMBEAU and A. RASSAT, Bull. Soc. Chim. Fr., 1970, 4404.
- (11) A. COULOMBEAU, Bull. Soc. Chim. Fr., 1970, 4407 ; Thesis, Grenoble 1968, CNRS, A.O.2767.
- (12) A.M. GIROUD and A. RASSAT, Bull. Soc. Chim. Fr., 1976, in print.
- (13) J.W. HUFFMAN, D.M. ALABRAN and T.W. BETHEA, J. Org. Chem., 1962, 27, 3381.
- (14) J.W. HUFFMAN, D.M. ALABRAN, T.W. BETHEA and A.C. RUGGLES, J. Org. Chem., 1964, 29, 2963.

- (15) J.W. HUFFMAN, and J.T. CHARLES, J. Amer. Chem. Soc., 1968, 90, 6486.
- (16) M. ALAUDDIN and M. MARTIN-SMITH, J. Org. Chem., 1963, 28, 886.
- (17) W.S. MURPHY and D.F. SULLIVAN, J.C.S. Perkin I, 1972, 999.
- (18) J. FRIED and N.A. ABRAHAM, Tetrahedron Letters, 1964, 1879.
- (19) F. SONDHEIMER, O. MANCERA, G. ROSENKRANZ and C. DJERASSI, J. Amer. Chem. Soc., 1953, 75, 1282.
- (20) S. BERNSTEIN, R. LITTELL, J.H. WILLIAMS, J. Amer. Chem. Soc., 1953, 75, 1481.
- (21) D.M.S. WHEELER and M.M. WHEELER, J. Org. Chem., 1962, 27, 3796.
- (22) D.M.S. WHEELER, M.M. WHEELER, M. FETIZON and W.H. CASTINE, Tetrahedron, 1967, 23, 3909.
- (23) B.R. ORTIZ DE MONTELLANO, B.A. LOVING, T.C. SHIELDS and P.D. GARDNER, J. Amer. Chem. Soc., 1967, 89, 3365.
- (24) D.D. KLEINFELTER, T.E. DYE, J.E. MALLORU and E.S. TRENT, J. Org. Chem., 1967, 32, 1734.
- (25) P.W. ATKINS and T.P. LAMBERT, Ann. Rep. Prog. Chem., 1975, 72, 67.
- (26) C. COULOMBEAU and A. RASSAT, Bull. Soc. Chim. Fr., 1970, 1199.
- (27) J. DOUADY, Y. ELLINGER, R. SUBRA, A. RASSAT and G. BERTHIER, J. Amer. Chem. Soc., 1975, 97, 476.
- (28) S. DINER, J.P. MALRIEU and P. CLAVERIE, Theoret. Chim. Acta, 1969, 13, 1 ; J.P. MALRIEU, P. CLAVERIE and S. DINER, Theoret. Chim. Acta, 1963, 13, 18 ; S. DINER, J.P. MALRIEU, F. JORDAN and M. GILBERT, Theoret. Chim. Acta, 1969, 15, 100 ; F. JORDAN, M. GILBERT, J.P. MALRIEU and U. PINCELLI, Theor. Chim. Acta, 1969, 15, 211.
- (29) Y. ELLINGER, Thesis, Grenoble 1973, C.N.R.S. A.O. 8167.
- (30) Y. ELLINGER, B. LEVY, P. MILLIE and R. SUBRA, in "Localization and Delocalization in Quantum Chemistry", O. CHALVET et al. Eds, vol. I, p.283, D. Reidel Publ. Co, Dordrecht-Holland, 1975.
- (31) for a review, see W. KUTZELNIFF (this Meeting).
- (32) A. RASSAT and P. REY, Tetrahedron, 1973, 29, 1599.
- (33) E. SCROCCO and J. TOMASI, Fortschr. Chem. Forsch., 1973, 42, 95.
- (34) Y. ELLINGER, R. SUBRA, G. BERTHIER and J. TOMASI, J. Phys. Chem., 1975, 79, 2440.
- (35) T.K. HA, Chem. Phys. Lett., 1975, 30, 379.
- (36) Y. BRUNEL, C. COULOMBEAU, H. FAUCHER, C. MORAT and A. RASSAT, Tetrahedron, 1973, 29, 233.
- (37) Y. BRUNEL, H. FAUCHER, D. GAGNAIRE and A. RASSAT, Tetrahedron, 1975, 31, 1075.
- (38) Y. BRUNEL, Thesis, Grenoble, 1973, C.N.R.S. A.O. 8417.
- (39) C. COULOMBEAU, Thesis, Grenoble, 1972, C.N.R.S., A.O., 6497.
- (40) C. COULOMBEAU and A. RASSAT, Tetrahedron, 1972, 28, 2299.
- (41) C. COULOMBEAU and A. RASSAT, Tetrahedron, 1972, 28, 751.
- (42) S.W. BENSON, Thermochemical Kinetics, Methods for the Estimation of Thermochemical Data, John Wiley and Sons Inc., New York, 1968, p. 39.
- (43) N.A. BELIKOVA, L.I. KOVALENKO, M.A. MOSKALEVA, M. ORDUBADU, A.F. PLATE, K.H.E. STERIN and R.S. YAGMINAS, Zh. Org. Khim., 1968, 4, 1363 ; N.A. BELIKOVA, L.I. KOVALENKO and A.F. PLATE, Zh. Org. Khim., 1970, 6, 1797.
- (44) G. KOMMPA, and S. BECKMANN, Annalen, 1936, 522, 137.
- (45) S. BECKMANN and R. METZGER, Chem. Ber., 1957, 90, 1564.