THE NATURE OF THE METAL–LIGAND BONDING IN THE COMPLEXES OF IONOPHORES WITH ALKALI METAL IONS. A QUANTUM MECHANICAL STUDY OF THE *N,N*-DIMETHYL ACETAMIDE AND METHYL ACETATE INTERACTION WITH Na^+ AND Li^+

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1. Introduction

Macrocyclic compounds, such as valinomycin, enniatins, nactins etc., forming lipophilic complexes with alkali metal ions (the so-called ionophores) are widely used in studying biochemical processes involved in membranous transport of ions [1–3]. Conformational aspects of the functioning of such compounds are well documented: X-ray methods have been employed to elucidate the three-dimensional structure of some crystalline ionophores [3, 4] and NMR and IR spectroscopy, circular dichroism and optical rotatory dispersion techniques etc. have furnished abundant information about the behaviour of these compounds in solutions [1, 2, 5]. It has been demonstrated that in ionophore complexes the cation is encaged in the organic molecule and remains there due to the ion–dipole interactions with the inwardly oriented polar groupings, e.g. ester, amide, ether etc.

Although this has been established, there are no unequivocal data on the nature of the interaction. Krasne and Eisenman [6] proposed an electrostatic model for metal–ligand interactions, with the charge on the alkali metal ion being assumed as +1 and the charges on the ligand group atoms estimated from the data on dipole moments. Simon and Morf [7] took into account polarization of ligands and also the contribution of quadrupole, repulsion and dispersion interactions. Julg laid the main emphasis on dispersion forces [8]. We believe that all these authors underestimate the donor–acceptor interactions accompanied by electron exchange between the cation and ligand groups. Ismaylov and Kruglyak [9] discussed these interactions in their study of metal ion solvation. Talekar and Sundaram [10] offered a quantum mechanical study of the structure of ionophore complexes with univalent cations, but they did not touch upon the possibility of the ion and ligand atoms sharing molecular orbitals.

In the present investigation the CNDO/2 semiempirical quantum mechanical method has been employed for studying metal–ligand interaction between dimethyl acetamide and methyl acetate (as models of ionophore ligands) and Na^+ and Li^+ ions

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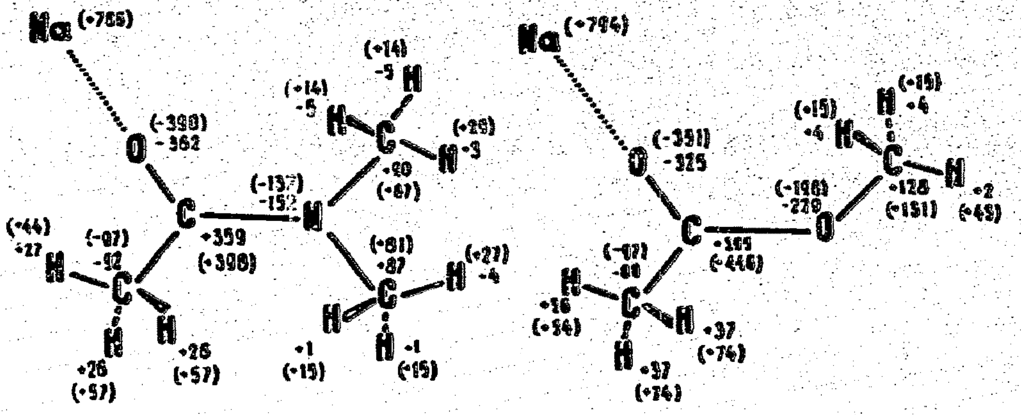

Fig. 1. Distribution of atomic charges in the molecules of a) dimethyl acetamide and b) methyl acetate in the absence (figures without brackets) and in the presence of sodium ions (figure in brackets). For obtaining the charges in electronic units these values should be divided by 1000.

2. Methods

The semiempirical quantum mechanical method approximated to a self-consistent field, CDNO/2, is described in detail by Pople et al. [12]. The method treats all valence electrons in the molecule and gives good results when one calculates net charges on atoms and geometrical parameters of various molecules [12, 13] including molecules of naturally occurring compounds [14, 15].

Molecules of dimethyl acetamide and methyl acetate were assumed as being rigid with bond lengths and valence angles from [14, 16]. Other parameters were borrowed from the work of Pople and Segal for hydrogen atoms and second row elements and from Satry and Segal for sodium atom with values of orbital exponents $Z_{S'} = 2.20$ and $Z_{D'} = 0.92$ [12].

The output from the program included: i) the total energy of the molecule; ii) the partial charges localized on each atom and iii) the Coulomb energy of interaction of the alkali metal atomic charge with the charges on all the other atoms. The latter value was calculated by means of the following formula:

$$U = 332 \sum_{A} \frac{q_{Me} q_{A}}{r_{Me-A}} ,$$

where r_{Me-A} is the distance between the centers of the alkali metal atom and the ligand group atoms, q_{Me} and q_A are the values of atomic charges.

3. Results and discussion

We began by computing net atomic charges in the molecules of dimethyl acetamide and methyl acetate in the absence (fig. 1, figures without brackets) and in the presence (figures in brackets) of the sodium ion localized in the direction of the C=O bond at a distance equal to the sum of the ionic radii of sodium and oxygen, 2.4 Å. This distance is characteristic of crystalline complexes of sodium with oxygen containing organic compounds [17]. As is seen in fig. 1, in the presence of sodium, distribution of atomic charges in the ligand groups markedly changes, and the sodium atom loses a part of its positive charge. This means that the metal–ligand interaction is not just electrostatic at a distance equal to the sum of the sodium and oxygen ionic radii, but has a more complicated nature due to the participation of the alkali metal ion in the formation of common molecular orbitals. In our case the position of the cation was fixed in a certain way. In a general case, as follows from an analysis of the stereochemistry of the natural complexes, the alkali metal cation may have different orientations with respect to the ligand group. Its position may be described by three parameters: r – the distance from the carbonyl group atom, θ – the angle between the metal, oxygen and carbon atoms, and φ – the angle between the C–O bond and the projection of the O–metal line onto the xOy plane (fig. 2). An analysis was made of the

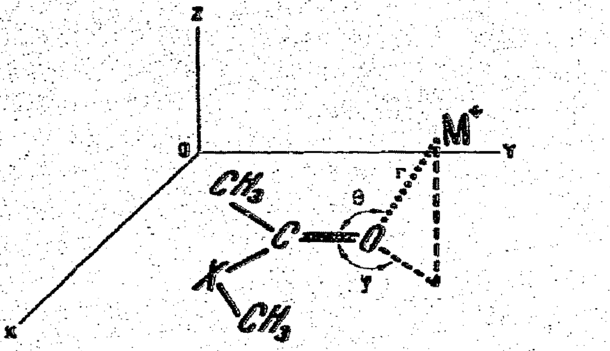

Fig. 2. Localization of the alkali metal cations ($M^+ = Li^+, Na^+$) with respect to the ligand groups of a) dimethyl acetamide $X{=}CH_3N{<}$ and b) methyl acetate X=O.

dependence of the change in the total energy, partial charge on the sodium atom and the Coulomb energy of interaction of this charge with other atomic charges in the complexed cations (Na-dimethyl acetamide)$^+$ and (Na-methyl acetate)$^+$ upon θ with φ = 180° (fig. 3). It was established that, as the sodium atom comes out of the ligand group plane, the Coulombic interaction between the metal atom charge with other atomic charges rapidly decreases because the sodium atom loses some of its positive charge; thereby the system loses its stability which is very well exemplified by methyl acetate. For comparison, the Coulombic interaction curves are also presented, calculated on the assumption that there is no charge transfer from the sodium atom to the ligand group. It is obvious that with such an assumption, which is hardly justified [6,7,10], quite different results may be expected.

The important feature of the dependence of the total energy on angle θ, is the presence of a minimum when the sodium atom considerably deviates from the ligand plane.

We have also studied the dependence of the total energy of cations (Na-dimethyl acetamide)$^+$ and (Na-methyl acetate)$^+$ on the distance between the sodium atom and that of the ligand oxygen (fig. 4). This dependence is a curve with a minimum localized at a distance of 3 Å. At the point of the minimum the atomic charge of sodium is about 0.8 electronic units and the metal–ligand interaction energy far exceeds the energy of electrostatic interaction of the sodium atomic charge with those of the ligand groups. These data should be interpreted to mean that the metal–ligand equilibrium distance interaction has the character of a chemical linkage, which is by 80% ionic and by 20% covalent as judged by the degree of the charge transfer. In the ionophore complexes, a still greater loss of the positive charge by the central atom should be expected, as several ligand groups are co-ordinated around it. This is evidenced, among

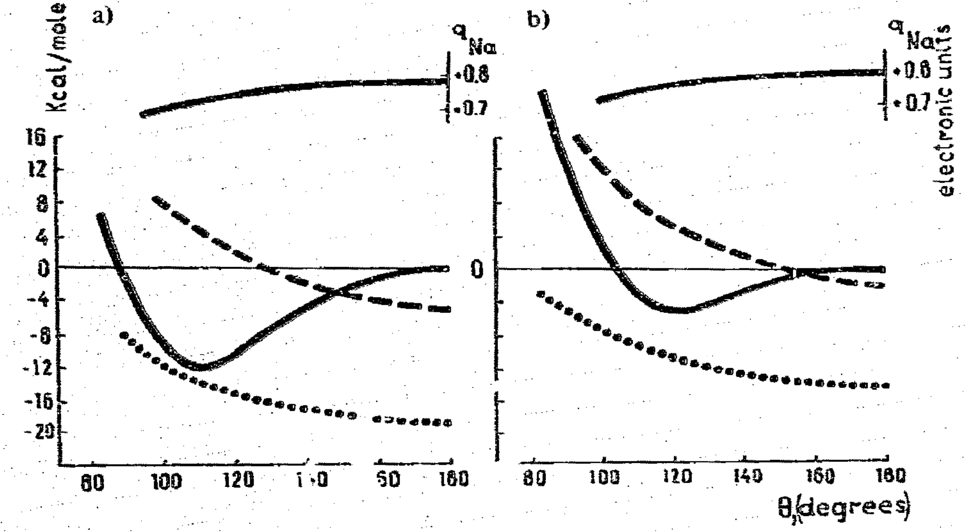

Fig. 3. Dependence upon the value of the θ angle of 1) change in the total energy of the system (——, curve with a minimum); 2) atomic charge on sodium (——, upper curve); 3) Coulombic interaction energy of the sodium atomic charge with those of other ligand atoms (----) and 4) Coulombic interaction energy (·····) neglecting charge transfer. r_{Na-O} = 2.4 Å, φ = 180° in the complex cations of a) (Na-dimethyl acetamide)$^+$ and b) (Na-methyl acetate)$^+$.

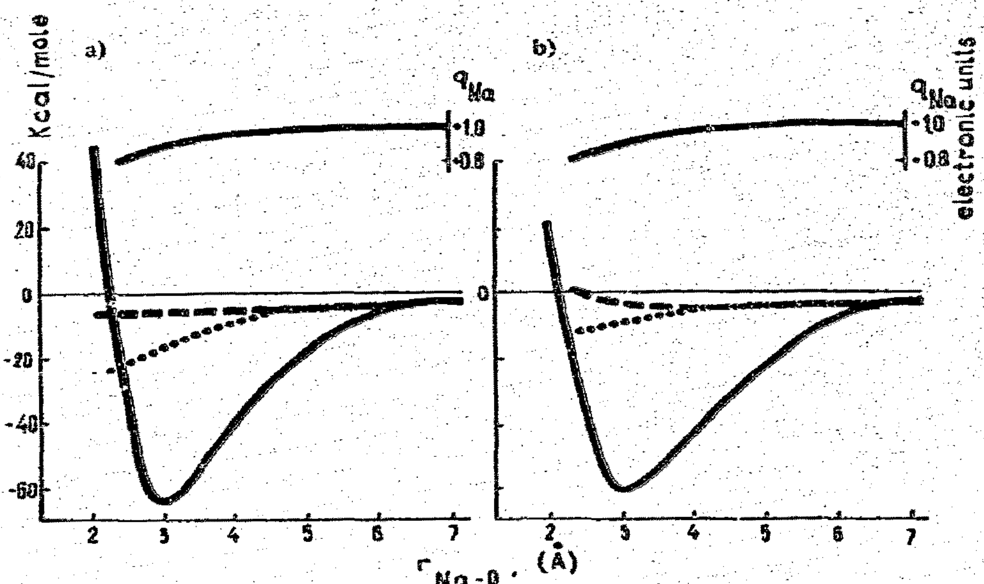

Fig. 4. Dependence of the same values as in fig. 3, $\theta = \varphi = 180°$ upon the r_{Na-O} distance in the complex cations of a) (Na-dimethyl acetamide)$^+$ and b) (Na-methyl acetate)$^+$.

other things, by calculated tetrahedral and octahedral models of alkali metal hydration [18]. At distances much larger than the sum of ionic radii, the metal–ligand interaction acquires a purely electrostatic character and coincides with the charge interaction curve (fig. 4). That the Na–O distance corresponding to the energy minimum exceeds by 0.2–0.3 Å the limits established for the sodium complexes with oxygen containing organic compounds [19] is, apparently, due to difficulties in accounting for the 3d orbitals of the third row elements.

With this in mind, we have carried out similar calculations for lithium with the same ligands. The results obtained thereby did not differ much, but the position of the minimum of the total energy shifted to 2.1 Å (fig. 5), which is in good agreement with the experimental value for the sum of ionic radii of lithium and oxygen [20, 21].

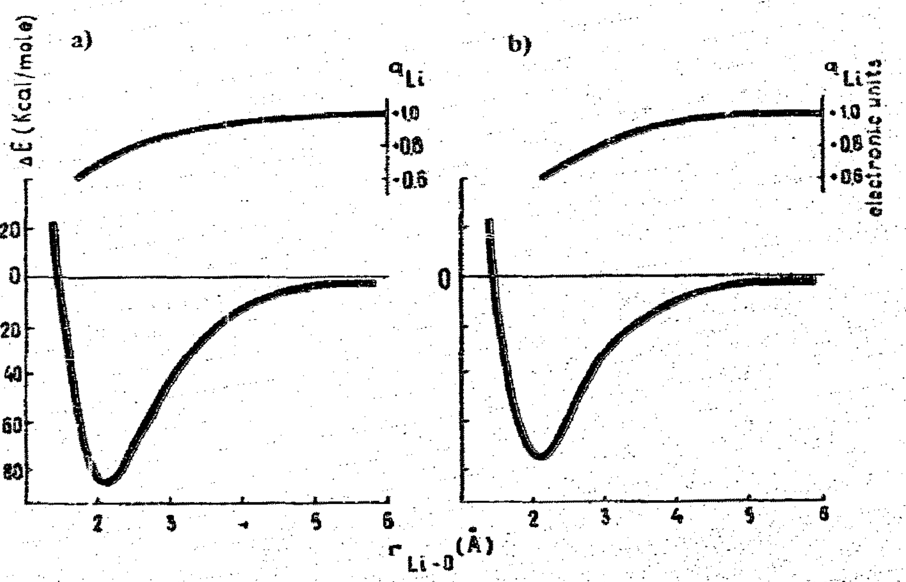

Fig. 5. Dependence of the total energy change (lower curve) and atomic charge on the lithium atom (upper curve) at $\theta = \varphi = 180°$ upon r_{Li-O} in the complex cations of a) (Li-dimethyl acetamide)$^+$ and b) (Li-methyl acetate)$^+$.

According to our data, the energy of the metal–ligand linkage in all the cases studied ranges from 60 to 80 kcal/mole and the amide and ester complex have an almost equal stability. Judging by the character of the groups involved in such interaction, the bond formed may be regarded as being of ion–dipole nature [21]. It follows from the results of the study of alkali metal cation complexes with the simplest ligands that natural ionophores should also have an ion–dipole bond.

For example, that the ionophore complexes with Li^+, Na^+, K^+, Rb^+ and Cs^+ have metal–ligand linkages have been proved by studying their far-infrared spectra, in which the bands corresponding to respective stretching vibrations were present [22]. This means that ionophore complexes are a new type of alkali metal complex compounds, whose cyclic molecules may be considered as a specific ligand of a high co-ordination capacity. We are now engaged in elaborating direct quantum mechanical approaches for studying such compounds.

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