

the calculation of the lattice energy of uncharged molecules and not necessary for charged molecules such as amino acids is not credible. Work in our laboratory (Greenberg, in preparation) on the energy of peptide crystals shows, as expected, that where the lattice energy is primarily determined by the nonbonded constants, the dielectric function makes no difference in the predicted crystal structure.

There is evidence from solution studies favoring the distance of 3.5 Å at which the step in the step function occurs and the discontinuous nature of the step itself. Theoretical studies on the free energy and entropy of hydration of ions in solution indicate that there is a discontinuity in ϵ at the edge of the first layer of water molecules surrounding an ion.²⁰ Furthermore, there is some evidence that the dielectric constant is the bulk value at distances from a hydrated ion of on the order of only 3 Å, depending on the size of the ion.²⁰ Other theoretical studies,²⁰ on the salting out behavior of ions, show that assuming a sharp cutoff after the primary hydration shell produces much better agreement with experiment than do continuum models (see also the review by Conway¹).

The above cited studies offer compelling corroboration of the present work. Despite the differing assumptions and approaches, these investigations revealed a sharp change in the dielectric constant at a critical distance related to the ion-water contact radius, results which exactly parallel the present findings in the crystalline state.

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- (21) Agreement between the experimental and calculated results for threonine is significantly worse than for the other amino acids. It was recently discovered that according to the x-ray data, the O-H bond length for the alcohol group is 1.4 Å, which is 0.4 Å longer than one would expect. The distance from the hydrogen to the carboxyl oxygen to which it is hydrogen bonded is 1.3 Å. It is unclear whether this is a mistake in the originally published data or a case of a hydrogen bond in which the hydrogen prefers to be closer to the oxygen to which it is hydrogen bonded than to its parent oxygen. In any case, the anomalous position of the hydrogen might explain the larger discrepancies in the threonine minimization compared to the other amino acids.
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Basis Set Dependence of Spatial Electron Distribution. Implications for Calculated Conformational Equilibria

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Abstract: The effect of deficiencies in the description of the spatial electron densities as calculated with minimal basis sets on conformational equilibria are described. Total electron density maps of *N*-methylacetamide for both minimal and extended basis sets and difference maps (extended minus minimal) are presented to demonstrate the difference in "atomic sizes" in the two basis sets. It is concluded that the "steric" effect, which is of major importance in determining conformation, is inadequately represented with minimal basis sets. A partitioning of the total energy supports these conclusions as well as further demonstrating that the main contribution to the barrier about the N-C α bond (ϕ) is the syn-planar H \cdots O steric repulsion.

In recent years there has been an ever-increasing number of molecular orbital calculations of molecular properties. Many of these calculations are directed toward the investigation of molecular structure and conformation.^{1,2} Conformation is of special interest in the case of biological molecules (or model compounds) because of the relation between conformation and

activity of these molecules.^{2c,3} In addition to the direct calculation of molecular conformation, several studies have recently appeared which propose the use of molecular orbital theory to obtain information about the (Born-Oppenheimer) energy surface of molecular systems for use in the development of analytical expressions for this energy surface.⁴ The latter ap-

Table I. Values of the Electron Density Contour Lines ($e/\text{\AA}^3$)

Symbol	Total density contours	Difference density contours
A	0.0067	0.000 067
B	0.0134	0.000 13
C	0.0268	0.000 27
D	0.0563	0.000 53
E	0.0107	0.001 05
F	0.213	0.002 10
G	0.425	0.004 20
H	0.847	0.008 37
I	1.69	
J	3.37	
K	6.73	
L	13.4	

Table II. Partitioning of the Barrier to Rotation about the N-C α Bond (ϕ) in NMA in 6-31G and STO-3G Bases^a

Energy component	$\Delta E = E_{120^\circ} - E_{180^\circ}$, kcal		$\Delta E_{6-31G} - \Delta E_{STO-3G}$, kcal
	6-31G	STO-3G	
Kinetic energy	10.44	7.83	2.61
Nuclear-electron	-141.63	-131.69	-9.94
Electron repulsion	71.25	63.34	7.91
Nuclear repulsion	60.55	60.55	0
Total	0.61	0.03	0.58

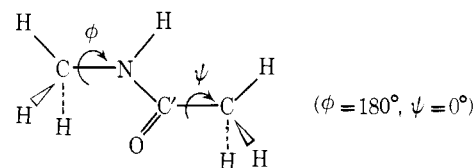
^a E_{120° , E_{180° are energies of NMA at $\phi = 120^\circ$ and $\phi = 180^\circ$. For definition of these conformations see Figure 1.

proaches are an attempt to combine the advantages implicit in the molecular orbital and empirical studies, which hitherto had been used exclusive of one another.^{2c,3b,c}

One of the major factors in determining the conformational energy minima of molecules is the "excluded volume" effect or "steric effect" which is directly related to the "size" of the interacting atoms.

In the present work we present results related to the rotational potential surface about the N-C α bond in *N*-methylamides. These results indicate that the electron density as described by minimal basis set ab initio calculations constrains the electrons to a region too close to the nucleus, resulting in atoms whose "radii" are too small. This can significantly affect the predicted stable conformations of molecules calculated with minimal basis sets. The difference in predicted stable conformations obtained with minimal and extended bases was demonstrated recently in a study of the energetics of rotation about the N-C α (ϕ) and C α -C' (ψ) bonds of methyl groups in amide and peptide systems.⁵ Ab initio molecular orbital calculations as carried out with a minimal STO-3G basis set⁶ yielded positions of the barrier and minima in the rotational potential surface for ϕ , in disagreement with the experimental data.⁷⁻¹⁰ The results of calculations with an extended basis set¹¹ (6-31G), on the other hand, yielded positions of the minima in agreement with the experimental observations.⁵

Analysis of the rotational energy surface in ϕ obtained with the empirical potential functions (which all gave the correct behavior of the ϕ potential surface), along with the quantum mechanical results, suggested that the difference in minimum energy conformation arose from the difference in the description of the electron density about the carbonyl oxygen in the two basis sets. In particular, it was suggested that the barrier to rotation arose mainly from the repulsion between oxygen and the methyl hydrogen in the cis configuration ($\phi = 0^\circ$ in Figure 1). The origin of the barrier was deduced both from the pairwise interatomic energy components in the empirical calculations and from the geometry dependence of the ab initio barriers.⁵ The difference in the barrier position in the two basis sets was then attributed to the greater volume occupied by the electrons in the extended basis set, which resulted

**Figure 1.** Definition of angles ϕ and ψ in *N*-methylacetamide (NMA). Experimentally observed conformation¹ of $\phi = 180^\circ$, $\psi = 0^\circ$.

in a greater repulsion between the oxygen and hydrogen atoms in this basis set.

In order to verify the inferred properties of the electron distribution in these compounds,¹² as well as the origin of the barrier, we have calculated the electron density distribution in *N*-methylacetamide (NMA) with both the minimal and extended basis sets. In addition we have calculated difference density maps by subtracting the electron density as calculated with the minimal basis from that calculated with the extended, in order to bring out the significant features of the difference between the two basis sets. Maps of the total electron density in the plane of the amide group as computed with the two basis sets are presented in Figure 2. In Figure 3 the difference density maps are presented, while in Figure 4 a three-dimensional perspective plot of the difference density is given. In the latter figure the viewer is looking along the carbonyl methyl group with the carbonyl group pointing to the upper right hand corner and the *N*-methyl in the left-hand corner of the map. (A key to the values of the contour lines is given in Table I.) In all electron density maps the NMA molecule is in the conformation shown in Figure 1. Lines connecting the atomic centers are drawn to help in orienting the figure, and where the atoms (methyl hydrogens) do not lie in the plane, the projection is drawn.

Inspection of the contours in Figure 3a shows that, as expected, there is a net positive difference density in the region surrounding¹³ the oxygen, at distances between ~ 1 and 3 \AA . This may also be seen clearly in the three-dimensional perspective plot as the positive region (a), at the back of the plot, indicating the excess electron density in this region in the extended basis (i.e., the oxygen is "larger" in this basis set). These maps also show a net positive density in the regions surrounding the methyl hydrogens [(b) and (c) in Figure 4], which would also contribute to the barrier at $\phi = 0^\circ$ for the same reasons outlined above. The region surrounding the amide hydrogen, on the other hand, shows a very small density in the extended basis relative to the minimal (Figure 2b and the valley between the two peaks b and c, i.e., region (d) in Figure 4), consistent with the fact that this bond is much more polar in the extended basis (Mulliken population analysis gives a charge on the amide hydrogen of +0.38 electrons in the extended compared with 0.20 in the minimal¹¹).

In order to further substantiate the arguments presented above, and to quantify the results pertaining to the origin of the barrier and its basis set dependence, we have partitioned the energy into its kinetic, nuclear-electron, electron-repulsion, and nuclear repulsion contributions. Analysis of these components should allow us to accomplish two objectives. We should gain further insight into the nature of the barrier itself, and, by comparing the components in the different basis sets, further document the origin of the basis set dependence. For example, it follows from the above discussion that the major contribution to the barrier at $\phi = 120^\circ$ should be the two-electron repulsion (corresponding to the H \cdots O repulsion found in the empirical calculations,⁵ and seen in the difference electron density maps).

The results of the partitioning for NMA are given in Table II. We present the difference in each component between the two conformations 120 and 180 $^\circ$, $E_{120^\circ} - E_{180^\circ}$ (see Figure

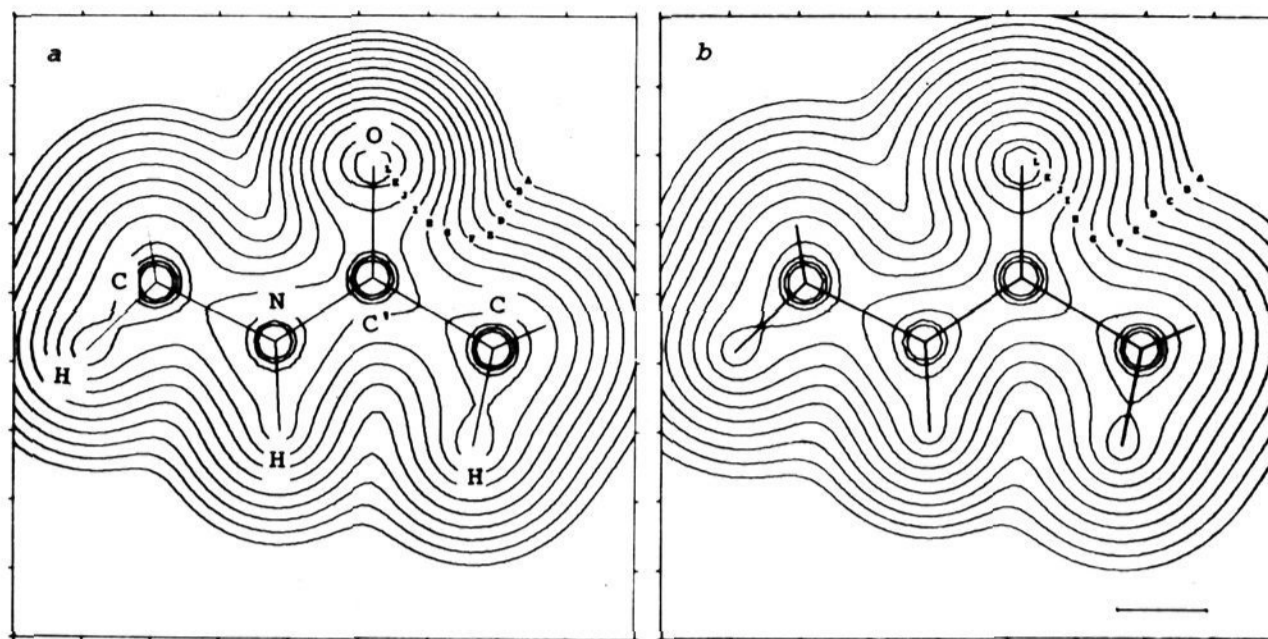


Figure 2. Total electron density contour maps of NMA in conformation shown in Figure 1, as calculated with (a) the extended 6-31G basis set and (b) the minimal STO-3G basis. Values of contour of constant density are given in Table I.

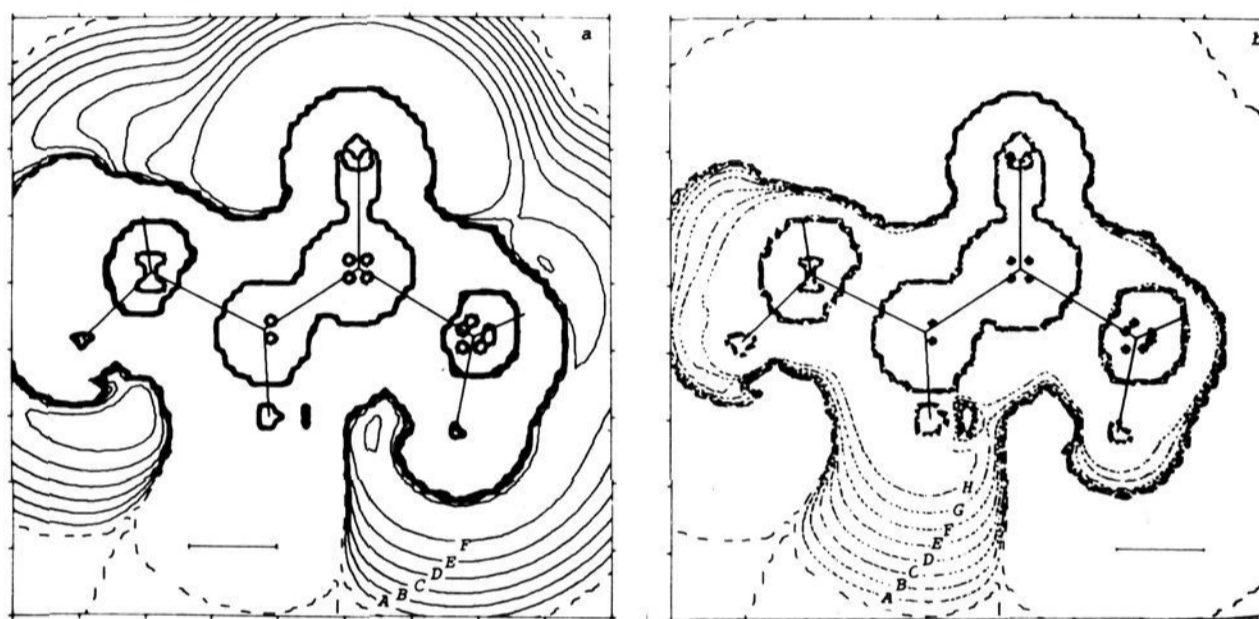


Figure 3. Difference electron density in NMA obtained by subtracting calculated density with minimal basis set from that calculated with the extended basis. Values of contours of constant density are given in Table I. (a) Positive difference density; (b) negative difference density.

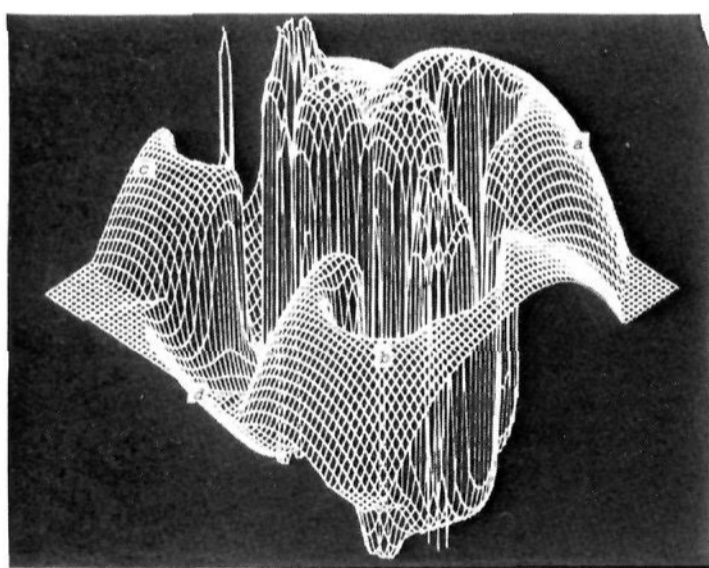


Figure 4. Three-dimensional perspective plot of extended minus minimal density contoured in Figure 3.

1), for both the 6-31G basis set and the minimal STO-3G basis set. The results of the partitioning in both basis sets confirm the conclusions as to the nature of the barrier as discussed above. Thus the two electron repulsions and the nuclear repulsion (which is independent of basis set) are both significantly larger at $\phi = 120^\circ$ corresponding to the O...H synplanar interaction, thus destabilizing this conformation. The kinetic energy is also slightly higher in this conformation further destabilizing it. The one electron potential energy, on the

other hand, tends to favor this conformation. The latter arises from the preference of the methyl hydrogen electrons to be synplanar to the more positive oxygen nucleus ($\phi = 120^\circ$), rather than to the amide proton ($\phi = 180^\circ$) and from the greater electron density about the oxygen, interacting with the methyl proton. Thus the observed equilibrium is due to a balance mainly between the electron and nuclear repulsions on the one hand which favor the observed conformation, and the nuclear-electron attraction which favors the 120° conformation.

The basis set dependence of the various energy components also substantiates the interpretation of the nature of the deficiency in the minimal basis set. Thus both the two-electron repulsion and nuclear-electron attractions are smaller in the minimal basis set owing to the smaller atoms in the latter. The decrement in the one-electron energy (including the kinetic energy), however, is not as large as the corresponding decrement in the two-electron repulsion, leading to the observed difference in stability of the different conformers in the different basis sets.⁵

Thus, analysis of the spatial electron density along with the partitioning of the total energy into its components in the different basis sets confirm the interpretation of the observed barrier about N-C α (ϕ) as being due to the H...O repulsion. Furthermore, they support the contention that differences in the electron density in the different basis sets, in particular, the spatial constraint on the electrons in the minimal basis set, can

lead to differences in the predicted stability of different conformers.

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- (1) By structure we refer to bond distances and bond angles, whereas molecular conformation refers to the relationships between atoms separated by three or more bonds.
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 - (13) In the discussion here, when "the region surrounding the atom" is used it refers to the periphery of the molecule, away from the bonds, and not into the bonding region.

Circular Dichroic Power Due to Chiral Exciton Coupling between Two Polyacene Chromophores

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Abstract: The CD spectra of (6*R*,15*R*)-(+)-6,15-dihydro-6,15-ethanonaphtho[2,3-*c*]pentaphene (**1**) and (7*R*,14*R*)-(+)-7,14-dihydro-7,14-ethanodibenz[*a,h*]anthracene (**2**) have been quantitatively calculated on the basis of a chiral exciton coupling mechanism between two anthracene or naphthalene chromophores. In the region of the allowed ¹B_g transition which is polarized along the long axis of chromophores, the CD spectra were satisfactorily reproduced by the quantitative calculation using the UV data of component chromophores. The calculation results have established the absolute stereochemistries of these compounds in a nonempirical manner. The exciton analysis of UV spectra has confirmed the above assignments. The CD spectra of the ¹L_a transition exhibit split Cotton effects of medium intensity, the sign of which has been explained by the point monopole approximation method. The calculation results have demonstrated the ideal examples of chiral exciton coupling and have established the unambiguity and reliability of the exciton chirality method.

In recent years, there has been a large amount of activity devoted to chiroptical properties of organic compounds which undergo chiral exciton coupling between two or more chromophores.¹⁻⁶ Namely, two identical or similar chromophores undergoing strong π-π* transitions electrostatically interact with each other to exhibit two strong CD Cotton effects of opposite sign and of same rotational strength. Provided that two electric transition moments make positive exciton chirality, i.e., right-handed screwness, a positive CD Cotton effect at the longer wavelength side is observed together with a negative one at the shorter wavelength side.

In our previous papers,⁷⁻⁹ we reported the synthesis and chiroptical properties of (6*R*,15*R*)-(+)-6,15-dihydro-6,15-ethanonaphtho[2,3-*c*]pentaphene (**1**) and (7*R*,14*R*)-(+)-7,14-dihydro-7,14-ethanodibenz[*a,h*]anthracene (**2**), the absolute configurations of which have been definitely determined by chemical correlations. These compounds exhibit very strong split CD Cotton effects due to the interaction between two anthracene or naphthalene chromophores. The results have demonstrated ideal cases of chiral exciton coupling in CD spectra, providing the most unambiguous evidence which demonstrates the consistency between nonempirical circular dichroic and x-ray Bijvoet methods.

The present CD exciton chirality method, which enables one to determine absolute configurations in a nonempirical manner, requires conservative Cotton effects of equal rotational

strength but of opposite sign. Namely, this method is applicable to the Cotton effects resulting only from the exciton coupling between two excitations (0 → a) of component chromophores without participation of other excited states (0 → b, etc.).¹⁰ Therefore, for performing the reliable assignment of absolute stereochemistries by the CD method, it is important to choose the proper electronic transition of proper chromophores satisfying the following requirements of chiral exciton coupling: (1) large extinction coefficient values in UV spectra; (2) isolation of the band in question from other strong absorptions; (3) established direction of the electric transition moment in the geometry of the chromophore; (4) unambiguous determination of the exciton chirality in space, inclusive of configuration and conformation; and (5) negligible molecular orbital overlapping between the chromophores.

In the present paper, we wish to report the quantitative calculation results of CD spectra of these compounds, confirming the previously reported qualitative assignment.⁷⁻⁹

Methods of Calculation

Molecular Structure. In the present calculation, the Cartesian coordinate systems for the molecular structures of compounds **1** and **2** are adopted as shown in Figure 1, in which the z axis is the C₂-symmetrical axis of these molecules. Geometric parameters were taken from the x-ray crystallographic data of triptycene and 9,10-ethanoanthracene deriv-