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Supplementary Material Available: Force constants of the uracil molecule, calculated on the STO-3G basis set, in comparison with what were empirically determined (2 pages).[4] Ordering information is given on any current masthead page.

VCNDO/S Method for Second-Row Atoms

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Abstract: A CNDO method has been constructed for the study of molecules containing second-row atoms. Empty, low-lying 3d orbitals are included, and the 3d orbital exponents, core integrals, and repulsion integrals involving X-ray orbitals are calculated after SCF convergence and used as input for a new SCF calculation. In this fashion the "size" and involvement of the 3d orbitals are calculated in a self-consistent manner for each molecule. Orbital occupations and calculated UV band maxima are presented for molecules containing sulfur.

Much has been written on the involvement of d orbitals in the chemistry of sulfur and other second-row elements.[1,2] The idea that d orbitals contract in an electron-withdrawing environment and thus become more effectively involved in bonding has been advanced[1,3] and has been under investigation in this laboratory since 1953.[3] Ab initio calculations with optimized scaling factors have shown that such factors for 3d orbitals on sulfur vary widely with the atoms to which the sulfur is bonded.[4] Binding energy, geometry, dipole moment, and other molecular properties are affected by the presence of d orbitals, particularly if the sulfur atoms would be strongly positive without their use.

CNDO level studies of molecules containing second-row elements have been reported, by many authors.[5-13] While most of these papers deal with ground-state properties of molecules, several attempts have been made to parameterize a CNDO method to reproduce spectroscopic data for molecules containing second-row atoms.[9,11-13]

However, none of the methods presented have incorporated adjustment of the size of the 3d orbitals to the electronegativity of the environment; this problem was first addressed here by Kuehnlenz.[14]

A method is presented here to extend the CNDO/S method to second-row elements; the heart of the method is a self-consistent optimization of 3d orbital exponents to account for the environment of the second-row element. This method has also been applied to CNDO/2 in a preliminary study.

Table I. Converged Values of Quantities Adjusted to Self-Consistency

	ζ_d	$\frac{1}{2}(I_d + A_d)$	orbital occupation		total charge on sulfur
			d	sp	
thiophenol	0.842	−11.085	0.16	6.11	0.27−
thioanisole	0.851	−10.795	0.27	6.06	0.32−
methyl *p*-aminophenyl thioether	0.850	−10.820	0.27	6.06	0.33−
methyl *p*-tolyl thioether	0.851	−10.812	0.27	6.06	0.33−
methyl phenyl sulfoxide	0.965	−7.705	0.56	5.52	0.08−
methyl phenyl sulfone	1.078	−0.965	1.59	4.50	0.10−
methyl merceptan	0.842	−11.059	0.15	6.10	0.26−
sulfur dioxide	1.053	−3.543	0.72	4.88	0.41+
thioformaldehyde	0.812	−11.766	0.10	6.23	0.34−
thiopyran-4*H*-one	0.868	−10.288	0.26	5.96	0.22−
pyran-4*H*-thione	0.781	−12.674	0.12	6.41	0.53−
thiopyran-4*H*-thione					
keto S	0.788	−12.479	0.12	6.37	0.50−
ring S	0.871	−10.184	0.26	5.95	0.20−
thiopyran-2*H*-thione					
keto S	0.798	−12.201	0.12	6.32	0.43−
ring S	0.879	−9.901	0.27	5.90	0.17−
thiophene	0.859	−10.528	0.26	6.01	0.27−
thiourea	0.767	−13.055	0.11	6.48	0.59−

Method

The method here developed is completely analogous to the method of Del Bene and Jaffe[15] as modified by Ellis, Kuehnlenz, and Jaffe.[16] For first-row atoms, all matrix elements are chosen exactly as described by these authors, except that for oxygen β° has been modified.[17]

For d orbitals, semiempirical integrals were made a function of the electron occupation of the secod-row atom; an iterative procedure is employed to calculate new parameters from the results of one iteration as input to the next. With use of Burns' rules,[18] at each iteration, ζ_d, the d orbital exponent, is calculated from the density matrix obtained in the previous iteration. ζ_d is then used to evaluate new I_d, A_d, $S_{\mu\nu}$, γ_{sd}, γ_{dd}, and $\beta_{\mu\nu}$. The value of the two-center integral, $\gamma_{\mu\nu}$, depends *only* on the atoms on which the atomic orbitals ϕ_μ and ϕ_ν are centered, and their azimuthal

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Table II. Singlet-Singlet Transition Energies (eV) in the Calibration Compounds

molecule	calcd (osc strength)	obsd	transition
thiophene[14-24]	4.98 (0.118)	5.16 (O-O bands)	$^1B_2, \pi^* \leftarrow \pi$
	5.68 (0.029)	5.99	$^1A_1, \pi^* \leftarrow \pi(n)$
	6.27 (0.011)	6.60	$^1B_1, \pi^* \leftarrow n$
	6.28 (0.015)		$^1B_1, \pi^* \leftarrow \pi$
phenol[24]	4.72 (0.004)	4.6 (0.020)[a]	$\pi^* \leftarrow \pi$
	5.90 (0.065)	5.8 (0.132)[a]	$\pi^* \leftarrow \pi$
	6.52		
	6.63 (0.965)	6.7 (0.636)[a]	$\pi^* \leftarrow \pi$
	6.65		
	6.67 (1.03)	6.9 (0.46)[a]	$\pi^* \leftarrow \pi$
thiophenol[24]	4.79	4.6 (0.013)[a]	$\pi^* \leftarrow \pi$
	5.92 (0.103)	5.3 (0.347)[a]	$\pi^* \leftarrow \pi$
	6.05 (0.048)		
	6.38		
	6.59 (1.114)	6.2 (0.398)[a]	$\pi^* \leftarrow \pi$
	6.65 (0.92)	6.8 (0.587)[a]	$\pi^* \leftarrow \pi$
methyl phenyl sulfoxide	4.78	4.5 (0.014)[a]	$\pi^* \leftarrow \pi$ ring
	5.88 (0.122)	4.9 (0.096)[a]	$\pi^* \leftarrow \pi$ ring
	6.04 (0.041)		CT
	6.30		
	6.55		
	6.57 (1.04)	6.2 (0.100)[a]	$\pi \leftarrow \pi$ ring
	6.63 (0.88)		$\pi \leftarrow \pi$ ring
methyl phenyl sulfone	4.80 (0.016)	4.70 (3.0)[b]	$\pi^* \leftarrow \pi$ ring
	5.52 (0.001)		CT
	5.88 (0.164)	5.71 (3.8)	$\pi^* \leftarrow \pi$ ring
	6.15 (0.008)		
pyran-4*H*-one[12]	3.00	4.00 (1.18)[b]	$^1A_2, \pi^* \leftarrow n$
	5.39 (0.11)	4.77 (5)[b]	$^1A_1, \pi^* \leftarrow \pi$
	5.28 (0.51)	5.21 (3.99)[b]	$^1B_2, \pi^* \leftarrow \pi$
thiopyran-4*H*-one[12]	2.88	3.90 (1.72)[b]	$^1A_2, \pi^* \leftarrow n$
	5.14 (0.596)	4.43 (4.15)[b]	$^1A_1, \pi^* \leftarrow \pi$
	5.59 (0.061)	5.64 (3.62)[b]	$^1B_2, \pi^* \leftarrow \pi$
pyran-4*H*-thione[12]	2.17	2.25 (1.26)[b]	$^1A_2, \pi^* \leftarrow n$
	3.67 (0.568)	3.76 (4.22)[b]	$^1A_1, \pi^* \leftarrow \pi(n)$
	4.10 (0.010)		$^1B_1, \pi^* \leftarrow \sigma$(keto)
	4.82 (0.028)		$^1B_2, \pi^* \leftarrow \pi(n)$
	5.07 (0.125)	5.39 (3.78)[b]	$^1B_2, \pi^* \leftarrow \pi$
thiopyran-4*H*-thione[12]	2.03	2.10 (1.43)[b]	$^1A_2, \pi^* \leftarrow n$
	3.73 (0.754)	3.26 (4.32)[b]	$^1A_1, \pi^* \leftarrow \pi(n)$
	4.01 (0.012)	4.28 (5)[b]	$^1B_1, \pi^* \leftarrow \sigma$
	4.84 (0.003)		$^1B_2, \pi^* \leftarrow \pi(n)$
	5.17 (0.102)	5.14 (3.34)[b]	$^1B_2, \pi \leftarrow \pi$
thiopyran-2*H*-thione[12]	1.91	2.10 (1.97)[b]	$\pi^* \leftarrow n$
	3.26 (0.385)	2.87 (3.73)[b]	$\pi^* \leftarrow \pi$
	4.11 (0.014)	3.90 (4.04)[b]	$\pi^* \leftarrow \sigma$
	4.85		
	4.95 (0.153)	5.17 (4.08)[b]	$\pi^* \leftarrow \pi$

[a] Oscillator strength. [b] log $\epsilon_{\max}$.

quantum number l, and consequently the method is *rotationally invariant*. All $\gamma_{\mu\nu}$ for the CNDO/S method are calculated by using Mataga–Nishimoto (2p-type) integrals, with one-center γ's as described below.

For the configuration $s^n p^m d^0$, which was chosen as the reference configuration

$$\mu\epsilon\{\mathrm{sp}\} \qquad U_{\mu\mu} = -\tfrac{1}{2}(I_\mu + A) - (Z_A - \tfrac{1}{2})\,\gamma_{AA}^{(\mathrm{ss})}$$

$$\mu\epsilon\{\mathrm{d}\} \qquad U_{\mu\mu} = -\tfrac{1}{2}(I_\mu + A_\mu) - Z_A\gamma_{AA}^{(\mathrm{sd})}$$

This differs from the treatment of Santry and Segal.[5] The elements of the Fock matrix under the approximations outlined above become

$\mu\epsilon\{\mathrm{sp}\}$

$$F_{\mu\mu} = -\tfrac{1}{2}(I_\mu + A_\mu) + \sum_B (P_B^{(\mathrm{s})} - Z_B)\gamma_{AB}^{(\mathrm{ss})} + P_B^{(\mathrm{d})}\,\gamma_{AB}^{(\mathrm{sd})}$$

$\mu\epsilon\{\mathrm{d}\}$

$$F_{\mu\mu} = -\tfrac{1}{2}(I_\mu + A_\mu) + \sum_B (P_B^{(\mathrm{s})} - Z_B)\gamma_{AB}^{(\mathrm{sd})} + P_B^{(\mathrm{d})}\gamma_{AB}^{(\mathrm{dd})}$$

$\mu,\nu\epsilon\{\mathrm{sp}\}$

$$F_{\mu\nu} = \tfrac{1}{2}(\beta^\circ{}_A^{(\mathrm{s})} + \beta^\circ{}_B^{(\mathrm{s})})(S_{\mu\nu}{}^\sigma + \kappa S_{\mu\nu}{}^\pi) - \tfrac{1}{2}P_{\mu\nu}\gamma_{AB}^{(\mathrm{ss})}$$

$\mu\epsilon\{\mathrm{d}\},\nu\epsilon\{\mathrm{sp,d}\}$

$$F_{\mu\nu} = \tfrac{1}{2}(\beta^\circ{}_A^{(\mathrm{d})} + \beta^\circ{}_B)\,(S_{\mu\nu}{}^\sigma + \kappa S_{\mu\nu}{}^\pi + S_{\mu\nu}{}^\delta) - \tfrac{1}{2}P_{\mu\nu}\gamma_{AB}^{(\mathrm{sd,dd})}$$

The ionization and electron affinities needed for $U_{\mu\mu}$ and for $\gamma_{AA}^{(\mathrm{ss})}$ are taken from Hinze and Jaffe,[25] and in each case the valence state used for the atom is the same as that used for the analogous first-row atom ($I_s + A_s = 30.57$, $I_p + A_p = 16.82$, $\gamma^{(\mathrm{ss})} = 10.01$ eV). $\beta^{\circ(\mathrm{s})}$ (−12.0 eV) and $\beta^{\circ(\mathrm{d})}$ (−4.0 eV) for sulfur have been parameterized against UV data[12,19-24] from a set of molecules representing widely diverse electronic environments. κ has been set to 0.585 for 3pπ overlap integrals as described for 2pπ integrals.[15]

Results and Discussion

Table I lists converged values of 3d orbital exponents ζ_d, 3sp and 3d occupations, and the semiempirical core integrals, $U_d = \frac{1}{2}(I_d + A_d)$ for 15 molecules containing sulfur. The U_d vary from −13.1 in thiourea to −0.96 in methyl phenyl sulfone and are

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repulsive. Scaling these to make them less repulsive seems to overstabilize the d orbitals, allowing too much d occupation in sulfoxides and sulfones. In molecules in which the sulfur is in a highly electron-withdrawing environment such as SOF_2 and SO_3 and ions such as $S_2O_3^{2-}$, SO_4^{2-}, U_d is positive (attractive). Both U_d and ζ_d show that in thiourea the d orbitals are extremely diffuse. The slight involvement of d orbitals in the sulfur atoms of thioketones is reflected in the small values ζ_d of thioformaldelyde and the thioketo sulfur atom of the pyranthiones. Little difference is seen between alkyl- and arylthiols in the contraction or occupation of the d orbitals. The S atoms in aryl thioether, with a 3d orbital exponent of 0.85, are similar to thiol sulfur. 3d occupations of 0.26–0.27 indicate a minimal degree of coupling between ring and methyl p orbitals through sulfur.

In thiophene, the $C_2 - C_3$ $p\pi$–$p\pi$ bond has a population of 0.27, compared with a population of 0.18 for the $d_{xz}\pi$–$p\pi$ and 0.03 for the $d_{xy}\pi$–p π "bonds". This is not surprising in view of the C–S bond length used in this calculation, which was the experimental value of 1.720 Å. As in S atoms in aryl thioethers, sulfur d orbitals have an occupation of 0.26 in thiophene, which indicates a minimal degree of coupling of the π-bond system through sulfur.

There is little difference between the calculated spectra of thiophenol and phenol (Table II). The transitions with appreciable oscillator strength are $\pi \rightarrow \pi^*$ involving ring orbitals almost exclusively. This means, as in phenol, the first transition (^1L_b) and the high-intensity transitions (^1B) in thiophenol are fairly well placed, but the (^1L_a) transition has failed to come down in energy. This pattern holds for the sulfoxide. The second ring $\pi \rightarrow \pi^*$ transition in thiophenol, observed at 4.9 eV, is calculated at 5.9 eV. In addition, there is a calculated charge-transfer band which is not seen in the experimental (liquid-phase) UV spectrum. The agreement between calculated and experimental spectra in the sulfone is good, although the intense band occurs at 5.9 eV in both thiophenol and methyl phenyl sulfone; the orbital nature of the states involved differs considerably in the two compounds.

In the pyran series of molecules in Table II, certain trends are apparent: first, in pyran-4*H*-one, the $^1A_1$ transition is calculated at an energy which is significantly too high. This also occurs in thiopyran-4*H*-one and seems to be a function of the keto group. The same effect is seen in both of the thiopyranthiones, although the disagreement is less pronounced. The $^1A_1$ transition in all these molecules involves transfer of electron density from the ring heteroatom to the ring double bonds.

Thus, the method developed appears to provide qualitative and semiquantitative insights into the special problems arising in the second period, especially those generated by the d orbitals.

Quantum Chemical and Statistical Thermodynamic Investigations of Anesthetic Activity. 1. The Interaction between Chloroform, Fluoroform, Cyclopropane, and an O–H···O Hydrogen Bond

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Abstract: It has been postulated that molecules having anesthetic potency are able to perturb or dissociate hydrogen bonds and that this is a factor in the mechanism of anesthesia. The equilibrium for a water dimer interacting with two potent anesthetics, chloroform or cyclopropane, and fluoroform, a molecule having no anesthetic potency, is examined by quantum chemical and statistical thermodynamic means. It is shown that the $\Delta G°$ values related to the "breaking" process and the extent of mixed dimer formation parallel the known anesthetic potencies of the three compounds.

I. Introduction

General anesthesia is a reversible perturbation of the nervous system. When an understanding of its mechanism is sought at the molecular level, two striking facts should be accounted for: (a) anesthetic action occurs without actual chemical reaction; (b) general anesthetics do not belong to any one common chemical type. Both facts indicate that the mechanism of anesthesia is connected with changes in molecular associations rather than the formation or breaking of covalent chemical bonds. While there seems to be general consensus on this point, the nature of the associations which are involved is still a subject for current investigations. (For recent reviews, see ref 4–8.)

For several years the theory adhered to by most researchers in the field was the unitary hypothesis based on interactions with the hydrophobic part of the cell membrane only. This originated with the well-known relationship between anesthetic potency and lipid solubility. In recent years, however, it became apparent that polar interactions are also important for the mechanism of anesthesia, especially if more potent anesthetics are involved.[9–21]

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