Intramolecular Hydrogen Bonding and Anomeric Interactions in $H_nXCH_2YH_m$ (XH_n, YH_m = OH, NH_2, SH, PH_2): A Global Conformational Analysis

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The global internal rotation potentials of the title compounds were obtained at the MP2/6-311+g(2d,p) level by scanning through the dihedral angles of the XH_n and YH_m functional groups with the remaining nuclear coordinates being energy minimized at the MP2/6-31G** level. The intramolecular hydrogen bonding between the XH_n and YH_m functional groups is represented by the general functional forms of the electric dipole−dipole, dipole−quadrupole, and quadrupole−quadrupole interactions. The through-direct-bond potentials between the functional group and its adjacent $-CH_2X$ or $-CH_2Y$ molecular fragment were represented by the conventional three Fourier terms. The general functional forms of these two types of potentials could adequately represent the global conformational potentials of these molecules. The present energy decomposition analysis suggests that both the electrostatic interactions and the charge delocalization interaction of the lone-pair electrons of the X or Y atom to its adjacent molecular fragment are equally important in determining the global conformational potentials, and the origin of the anomeric effect of these compounds could be quantitatively explained in terms of these two types of interactions. Quantitative comparisons of the anomeric interaction strengths and the related orbital interaction energies among the title compounds were emphasized. Their general implications on the related molecular systems reported in the literature were also discussed.

1. Introduction

The conformations, along with their intramolecular hydrogen bonding (H-bonding) and anomeric interactions, of the molecular systems $H_nXCH_2YH_m$ (XH_n, YH_m = OH, NH_2, SH, PH_2) have been studied intensively for some years.[1] Along the course, in order to understand the nature of the anomeric interactions, a number of energy decomposition schemes for analyzing the conformational energies of these prototype compounds have been developed.[2−17] Despite the effort, there is still a lack of a generally accepted, unified picture of the anomeric effect, especially when one tries to compare the relative strengths of the effect among these molecules. For these simple model systems, the main problem comes from the fact that there is always some intramolecular H-bonding (or electrostatic interaction) contribution, which could be either positive or negative, to the observed anomeric effect. A quantitative representation of the electrostatic energies was required to resolve the controversy surrounding the roles of electrostatic and charge delocalization interaction in the manifestation of the observed anomeric effect. Nevertheless, it is also well recognized that there is some degree of arbitrariness in decomposing the total interaction energy into electrostatic energy plus some other energy interaction terms.[1a,8,18] Alternatively, one may turn to the orbital interaction energies (or charge delocalization energies) of the molecules for a resolution. However, depending on the calculation methods, either the electrostatic interaction energies were not explicitly represented or only limited approximate orbital interaction energies were available for comparisons among the molecular systems.[2−16]

In a series of studies on the global conformational potentials of one-carbon compounds (methanediol, methanediamine, and aminomethanol) and also two-carbon compounds (1,2-ethanediamine, 1,2-ethanediol, and 2-aminoethanol) it has been demonstrated that their global conformational potentials could be quantitatively represented by two types of general functional forms.[17,19] One is the through-space intramolecular H-bonding between the two functional groups and could be adequately represented by the general electrostatic multipole interactions. The other is the through-direct-bond interactions between the adjacent molecular fragments and could be represented by the conventional forms of the Fourier series as a function of the torsion angles. Since the present energy representation is specific in both the conformational dependency of the interactions and the interaction functional forms, one could decompose the intramolecular interaction strengths into the electrostatic and orbital interaction energies in an unambiguous and quantitative way.

In this report, the global ab initio internal rotation potentials of the title compounds were calculated over the whole range of the internal rotation angles of the two functional groups, with the remaining nuclear coordinates being energy minimized. The ab initio conformational potentials were then fitted with the full form of the electric dipole−dipole, dipole−quadrupole, and quadrupole−quadrupole interactions between the two functional rotors plus the conventional three Fourier interaction terms between the functional groups and their adjacent molecular fragment. The origin of the anomeric effect of these molecules could be quantitatively interpreted in terms of the present conformational energy decomposition scheme. On the basis of the present results, a general discussion on the related works in the literature was also given.

2. Computational Procedure

2a. Ab Initio Conformational Potentials, Atomic Charges, Atomic Dipoles, and Atomic Quadrupoles. Ab initio molec-

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ular orbital calculations were carried out by the *Gaussian 94* program package.[20] The geometrical parameters were determined at the MP2(fu)/6-31g(2d,p) level. The energies were all calculated up to the MP2(fu)/6-311+g(2d,p) level. The results of methanediol, methanediamine, and aminomethanol have been reported in a previous publication and are adapted directly in this report.[17]

The conformational notations of these molecules are in accord with the convention in the literature. The g (gauche), g′ (anti-gauche), and t (trans) symbols are employed. In the case of the amino and phosphino groups, the conformation is referred to the position of the lone-pair electrons. The final conformation would be read as tg, gg, etc., in which the first conformation notation refers to the first functional group and the second one refers to the second functional group according to their written order in the formal name. Specifically, for the present heterofunctional molecules, they are aminomethanol (H_2NCH_2OH; NO), aminomethanethiol (H_2NCH_2SH; NS), aminomethanephosphine ($H_2NCH_2PH_2$; NP), hydroxymethanephosphine ($HOCH_2PH_2$; OP), mercaptomethanephosphine ($HSCH_2PH_2$; SP), and hydroxymethanethiol ($HOCH_2SH$; OS). The other four homofunctional molecules, methanediol, methaediamine, methanedithiol, and methanediphosphine, are abbreviated as OO, NN, SS, and PP, respectively.

All of the possible locally stable conformers were located at the specified calculation level. Their geometric parameters, harmonic vibrational frequencies, and energies were calculated. The minimum energy paths, in which the dihedral angle of one functional group was varied while the initial conformation of the other functional group was set in the general gauche position, were then calculated. All of the nuclear coordinates which were not specified were energy minimized. These minimum energy paths also served as a standard for the comparison between the ab initio and the fitted potentials.

Starting from the (0,0) conformation, in which the first value indicates the dihedral angle of the first functional group and the second value indicates the dihedral angle of the second functional group, the two torsional angles were scanned at an interval of 30° over the whole conformation. Including the data points of the minimum energy paths which were sampled at an interval of 20° and local minima, a total of about 90 independent potential points were calculated for each of the molecules.

The theoretical atomic charges, atomic dipoles and atomic quadrupoles were calculated by the local density functional method (DMol)[21] with the Hirshfeld partition at the double numerical basis functions augmented with polarization functions.[22,23] Since the molecular fragments, such as $-CH_2-$ and $-XH_n$, instead of the individual atoms were considered in this study, the theoretical dipole moments and quadrupole moments of the molecular fragments were calculated from the atomic multipole moments according to their formal relations.[22,23]

2b. General Functional Form of the Conformational Potentials. The general procedure for a functional representation of the conformational potentials has been reported elsewhere.[17,19] Only a brief description was given here. The conformational potentials of the two functional groups as in the form of the two coupled internal rotors was approximated by the following functional form:

$$V(\omega_a,\omega_b) = V_a(\omega_a) + V_b(\omega_b) + V_o + V_{dd}(\omega_a,\omega_b) + V_{dq}(\omega_a,\omega_b) + V_{qq}(\omega_a,\omega_b) \quad (1)$$

with

$$V_a = \frac{1}{2}\{v_1(1 + \cos\omega_a) + v_2[1 - \cos(2\,\omega_a)] + v_3[1 + \cos(3\,\omega_a)]\} \quad (2)$$

$$V_b = \frac{1}{2}\{v_4(1 + \cos\omega_b) + v_5[1 - \cos(2\,\omega_b)] + v_6[1 + \cos(3\,\omega_b)]\} \quad (3)$$

in which ω_a and ω_b are the dihedral angles of the two functional groups defined in the range of 0° to 360°; V_a, and V_b are the decoupled potentials of the two functional groups; V_o is a constant; v_i are fitted parameters, and V_{dd}, V_{dq}, and V_{qq} are the electric dipole−dipole, dipole−quadrupole, and quadrupole−quadrupole interaction terms, respectively, between the two functional groups located separately at the X and Y atoms. In this report the summation of $V_a(\omega_a)$, $V_b(\omega_b)$, and V_o is referred as the decoupled rotor potential. The details of the general functional forms of V_{dd}, V_{dq}, and V_{qq} are reported in a previous publication.[17]

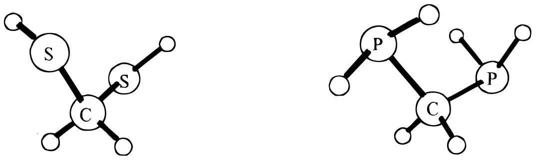
There are three main predetermined parameters in this study. Here, θ_d is the azimuthal angle of the dipole moment of the functional group with respect to the internal rotation axis and was calculated directly from the Hirshfeld dipole moments of the fragment, r is the interdipole distance, and α is the angle between the interdipole vector and the rotation axis of the internal rotor, and both were determined from the average theoretical geometric parameters of the stable conformers of the molecules. The rest of the parameters, such as the dipole and quadrupole moments or the dipole−quadrupole moment products, and the six v_i parameters were determined through the nonlinear least-squares fitting procedure. Depending on the dependency among the fitted parameters, for some heterofunctional compounds, the azimuthal angles of the quadrupole moments were adapted directly from the fitted values of the corresponding homofunctional compounds.

3. Results and Discussion

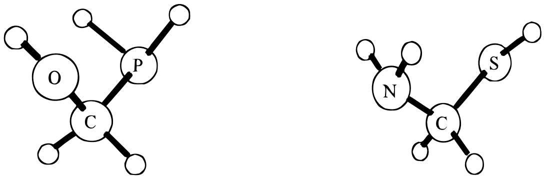
3a. Structures and Energies of Stable Conformers. Figure 1 shows the schematic structures and their conformation notations for the most stable conformers of the seven major compounds considered in this report. Table 1 lists all of the locally stable conformers and their relative conformational energies along with their vibrational zero-point energy corrections. The data of methanediamine, methanediol, and aminomethanol are adapted directly from a previous study.[17]

For these molecules, the primary geometric parameters among their stable conformers are quite close to each other. For example, in the case of NS, the C−N and C−S bond distances are within 0.5% and 1% of the average bond distance 1.447 and 1.826 Å, respectively, and the S−H bond distances are within 0.1% of the average bond distance 1.331 Å among the five stable conformers at the MP2/6-31g** level. The largest variation comes from the NCS angle, which is within 6° of the average NCS angle of 112.1° among these five conformations. The remaining six compounds show similar geometric characteristics. The average values of the primary geometric parameters of the stable conformers were used as the basic structural parameters of the compounds in this study.

The bottom parts of Tables 2, 3, and 4 show average values of the structural parameters for SS, PP, and NS. Their standard deviations over the stable conformers are all in reasonably small values. Similar magnitudes are also observed in the rest of the molecules. Clearly, these parameters are adequate in representing

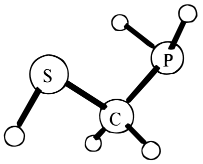


Methanedithiol (*gg*) Methanediphosphine (*gt*)



Hydroxymethanephosphine (*gt*) Aminomethanethiol (*tg*)

Aminomethanephosphine (*tt*) Hydroxymethanethiol (*gg*)



Mercaptomethanephosphine (*tt*)

Figure 1. Schematic diagram and the notation for the most stable conformer of each compound considered in this report.

TABLE 1: Relative Conformational Energies of the Stable Conformers of $H_nXCH_2YH_m$

compd	X	Y	con-former	HF[a] (kcal/mol)	MP2[b] (kcal/mol)	ZPEC[c] (kcal/mol)	msc[d]
1	S	S	gg	0.00	0.00	0.00	H: −835.279356
			gt	0.73	1.14	−0.11	M: −836.023852
			g′g	1.14	1.19	−0.19	Z: 30.45
			tt	2.68	3.11	−0.29	
2	P	P	gt	0.00	0.00	0.00	H: −722.847461
			tt	0.64	0.49	−0.003	M: −723.568414
			g′g	0.88	0.98	−0.04	Z: 41.03
			gg	0.74	1.00	−0.06	
3	O	P	gt	0.00	0.00	0.00	H: −456.401188
			tt	0.15	0.41	−0.18	M: −457.092186
			g′g	0.51	1.10	−0.05	Z: 38.99
			tg	1.24	1.96	−0.28	
			gg	1.56	2.04	−0.11	
4	N	S	tg	0.00	0.00	0.00	H: −492.789116
			tt	0.61	1.27	−0.11	M: −493.469421
			gg′	0.25	1.41	−0.08	Z: 41.91
			gt	2.77	3.34	−0.13	
			gg	3.04	3.37	−0.32	
5	N	P	tt	0.00	0.00	0.00	H: −436.566518
			gt	−0.03	0.19	−0.07	M: −437.235555
			tg	0.34	0.86	−0.07	Z: 46.98
			gg	0.18	0.92	−0.05	
			gg′	1.08	1.57	−0.08	
6	O	S	gg	0.00	0.00	0.00	H: −512.624170
			g′g	1.54	1.56	−0.18	M: −513.326985
			tg	2.95	3.20	−0.40	Z: 33.65
			gt[e]	2.88	3.68	*e*	
			tt[e]	5.13	6.16	*e*	
7	S	P	tt	0.00	0.00	0.00	H: −779.063288
			gt	0.56	0.32	0.08	M: −779.795422
			g′g	0.23	0.35	0.06	Z: 35.84
			gg	0.66	0.64	0.04	
			tg	1.34	1.60	−0.05	

[a] HF/6-311+g(2d,p). [b] MP2(fu)/6-311+g(2d,p). [c] Zero-point energy correction. [d] The HF (H), MP2 (M) (in a.u.) and vibrational zero-point energy (*Z*) (in kcal/mol) of the most stable conformer (msc). [e] Locally unstable, calculated at (60,180) and (180,180), respectively.

TABLE 2: Fitted and Structural Parameters of Methanedithiol

	value	σ[a]	D[b]	units
	fitted parameters			
μ	3.41	0.13	0.51	$(Å^3\,kcal/mol)^{1/2}$
q	23.8	0.51	0.39	$(Å^4\,kcal/mol)^{1/2}$
v_1	−0.836	0.05	0.83	kcal/mol
v_2	−0.762	0.04	0.82	
v_3	1.583	0.04	0.73	
V_0	2.530	0.09	0.94	
θ_q	73.3	1.42	0.78	degrees
	structural parameters			
r	3.03 ± 0.08			Å
θ_d	94.9 ± 1.9			degrees
α	146.6 ± 2.1			

[a] Standard errors of the fitted parameters. [b] Dependence = 1 − (variance of the parameter, other parameters constant)/(variance of the parameter, other parameters changing).

the basic geometric structures of the conformers in the present molecular systems.

3b. Global Conformational Potentials and the Relationship with the Theoretical Local Dipole and Quadrupole Moments. Starting with the homofunctional compounds of SS and PP, with the structural parameters r, α, and θ_d being set to the average values of their stable conformers, the global ab initio potentials were least-squares fitted with eq 1. The structural and the best-fitted parameters, along with their asymptotic standard errors and the dependence, are listed in Tables 2 and 3. The fitted θ_q values of the mercapto and phosphino groups are then used as additional structural parameters for the related heterofunctional molecules except for the mercapto group in OS and NS. For the latter two molecules, the lower dependence among the fitted parameters allowed an unambiguous determination of θ_q. Taking the NS molecule as an example, its structural and best-fitted parameters are shown in Table 4. The fitted and structural parameters of the remaining four molecules are tabulated in the Supporting Information.

The global average energy deviations between the ab initio and the fitted potentials for the seven compounds are 0.19 (SS), 0.30 (PP), 0.15 (OP), 0.22 (NS), 0.20 (NP), 0.18 (OS), and 0.20 (SP) kcal/mol. More specifically, here, we take the NP molecule as an example. Figure 2(a and b) shows the minimum energy paths of NP with $-PH_2$ being initially positioned in the general either g or t conformations, respectively, and $-NH_2$ rotating from 0° to 180° or 360°. The nuclear coordinates not being numerically specified were energy minimized. The full curves represent the ab initio potentials and the dashed lines are the fitted potentials. The dihedral angles and the relative energies of the five local conformation minima of the ab initio potential are (180, 180) 0.00; (60.6, 186.2) 0.19; (182.6, 56.9) 0.86; (−48.6, 64.8) 1.57; and (56.0, 52.1) 0.90, respectively, in the format of (NH_2 angle, PH_2 angle) kcal/mol. The corresponding values calculated from the fitted potential are (180, 180) 0.07; (62.3, 188.3) 0.11; (180.4, 56.5) 0.74; (−49.2, 65.3) 1.75; and

TABLE 3: Fitted and Structural Parameters of Methanediphosphine

	value	σ^a	D^b	units
	fitted parameters			
μ	0.148	0.078	0.98	(Å^3 kcal/mol)$^{1/2}$
q	−13.7	0.96	0.94	(Å^4 kcal/mol)$^{1/2}$
v_1	0.533	0.107	0.92	kcal/mol
v_2	−0.245	0.069	0.82	
v_3	2.279	0.062	0.69	
V_0	0.019	0.163	0.96	
θ_q	115.2	11.79	0.95	degrees
	structural parameters			
r	3.13 ± 0.09			Å
θ_d	103.3 ± 1.9			degrees
α	146.6 ± 2.2			

[a] Standard errors of the fitted parameters. [b] Dependence = 1 − (variance of the parameter, other parameters constant)/(variance of the parameter, other parameters changing).

TABLE 4: Fitted and Structural Parameters of Aminomethanethiol

	value	σ^a	D^b	units
	fitted parameters			
$\mu_{NH_2}\mu_{SH}$	16.8	3.85	0.98	Å^3 kcal/mol
$\mu_{NH_2}q_{SH}$	123.3	6.08	0.60	Å^4 kcal/mol
$\mu_{SH}q_{NH_2}$	−44.8	3.21	0.98	
v_1	1.927	0.07	0.65	kcal/mol
v_2	1.965	0.07	0.63	
v_3	2.479	0.07	0.59	
v_4	−0.336	0.11	0.85	
v_5	−2.046	0.07	0.69	
v_6	1.483	0.07	0.64	
V_0	1.475	0.11	0.95	
θ_{qSH}	78.2	4.20	0.95	
	structural parameters			
r	2.72 ± 0.07			Å
θ_{dSH}	105.5 ± 3.9			degrees
θ_{dNH_2}	66.2 ± 3.7			
θ_{qNH_2}	105.7 ± 2.7			
α_{NH_2}	141.6 ± 2.3			
α_{SH}	29.5 ± 1.8			

[a] Standard errors of the fitted parameters. [b] Dependence = 1 − (variance of the parameter, other parameters constant)/(variance of the parameter, other parameters changing).

(56.0, 53.3) 0.90, respectively. Apparently, the global agreement between these two types of potential is very good. Overall, except for the case of PP, in which a slightly larger energy discrepancy was observed in some local region of the conformational potential, the agreement between the ab initio and fitted potential is also very good for the rest of the molecules with similar energy deviations.

One naturally would wonder whether the decoupled rotor terms or the electrostatic terms alone would be good enough to represent the ab initio potential. Taking the intermediate case of the NP system as an example, one could find that there are no ways that the electrostatic terms alone could reasonably fit the ab initio potential. In the case of the decoupled rotor terms, as compared with the above normal values, the global energy standard deviation would increase from 0.20 to 0.36 kcal/mol and the maximum local energy deviation would increase from 0.62 to 0.92 kcal/mol. The range of less well-fitted conformations would also increase appreciably. Note that the low dependency among the fitted parameters as shown in Tables 2 and 3 also supports the necessity to include both interaction terms in the full potential representation.

Although the global agreement between the ab initio and fitted energies is generally excellent, there are still some minor energy deviated points. Several possible factors could contribute to the deviations: (a) the inadequacy of the assumed cylindrically symmetric quadrupole potential form, (b) the possible contributions from higher multipole potentials, (c) the possible coupling terms between the electrostatic interactions and the decoupled rotor potentials and/or between the two decoupled rotor potentials, and (d) the possible subtle variations of the energy due to the variations of the nuclear coordinates in the energy minimization procedure which were not properly approximated with the present potential functional forms. An unambiguous estimation of these additional minor perturbation factors is not possible under the present energy representation scheme.

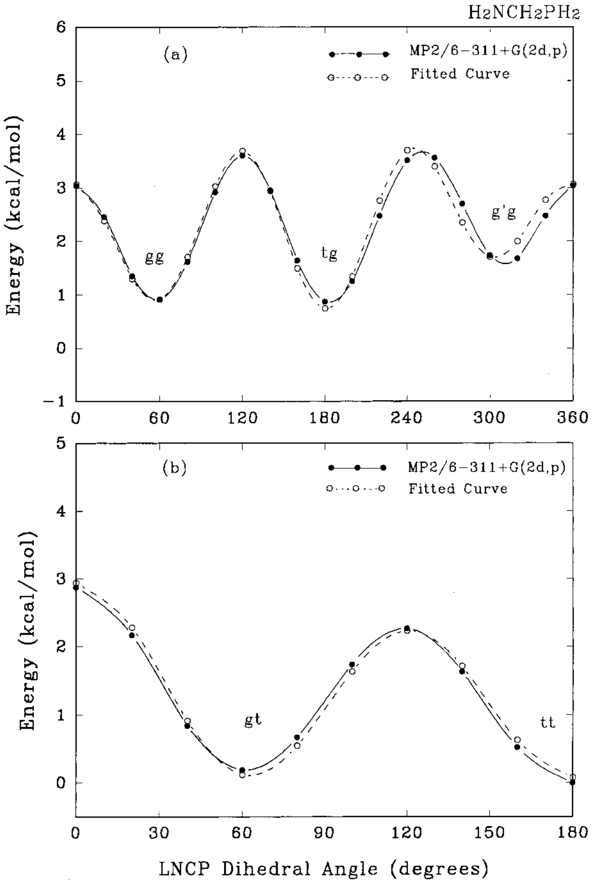


Figure 2. Minimum energy paths of (*x*,g) (a) and (*x*,t) (b) of aminomethanephosphine, in which the *x* indicates the variation of the amino dihedral angle, and the phosphino group was geometrically optimized in the general g and t conformations, respectively. The solid lines are the ab initio potentials and the dashed lines are the corresponding fitted potentials.

TABLE 5: Dipole and Quadrupole Moments of Homofunctional Molecules

compd	molecular groups	theor. dipole^a	fitted dipole^a	theor. quadrupole^b	fitted quadrupole^b
$CH_2(OH)_2$^{c}	OH	1.43	1.49	4.48	3.37
$CH_2(SH)_2$	SH	0.71	0.90	5.41	6.27
$CH_2(NH_2)_2$^{c}	NH_2	1.45	1.37	−3.18	−3.85
$CH_2(PH_2)_2$	PH_2	0.64	0.04	−3.08	−3.60
$HOCH_2CH_2OH$^{d}	OH	1.40	1.35	4.09	3.21
$H_2NCH_2CH_2NH_2$^{d}	NH_2	1.42	1.26	−3.20	−2.96

[a] Units: 10^{-18} esu cm. [b] Units: 10^{-26} esu cm^2. [c] Reference 17. [d] Reference 19.

Table 5 lists the dipole and quadrupole moments of the functional groups for the homofunctional compounds. Table 6 lists the products of the dipole and quadrupole moments of the heterofunctional compounds. For comparison, the related amino-

TABLE 6: Products of the Dipole and Quadrupole Moments of Heterofunctional Molecules

compd	molecular groups	$d \times d^a$		$d \times q^b$	
		theor.	fitted	theor.	fitted
$HOCH_2SH$	$d_{OH} \times d_{SH}$	1.05	1.20		
	$d_{OH} \times q_{SH}$			8.23	9.73
	$d_{SH} \times q_{OH}$			3.07	2.68
$HOCH_2PH_2$	$d_{OH} \times d_{PH_2}$	0.93	0.87		
	$d_{OH} \times q_{PH_2}$			−3.86	−5.49
	$d_{PH_2} \times q_{OH}$			2.88	1.73
H_2NCH_2SH	$d_{SH} \times d_{NH_2}$	1.04	1.17		
	$d_{SH} \times q_{NH_2}$			−2.49	−3.11
	$d_{NH_2} \times q_{SH}$			7.97	8.56
$H_2NCH_2PH_2$	$d_{PH_2} \times d_{NH_2}$	0.95	0.77		
	$d_{PH_2} \times q_{NH_2}$			−2.10	−1.95
	$d_{NH_2} \times q_{PH_2}$			−4.82	−5.34
$HSCH_2PH_2$	$d_{SH} \times d_{PH_2}$	0.44	0.21		
	$d_{SH} \times q_{PH_2}$			−1.92	−2.05
	$d_{PH_2} \times q_{SH}$			3.43	2.12
H_2NCH_2OH[c]	$d_{OH} \times d_{NH_2}$	2.06	2.13		
	$d_{OH} \times q_{NH_2}$			−4.92	−6.42
	$d_{NH_2} \times q_{OH}$			6.39	4.49
$H_2NCH_2CH_2OH$[d]	$d_{OH} \times d_{NH_2}$	1.97	2.18		
	$d_{NH_2} \times q_{OH}$			6.16	5.30
	$d_{OH} \times q_{NH_2}$			−4.32	−6.63

[a] Units: 10^{-36} esu^2 cm^2. [b] Units: 10^{-44} esu^2 cm^3. [c] Reference 17. [d] Reference 19.

and/or hydroxy-disubstituted compounds of methane and ethane reported in previous publications were also listed.[17,19] In the case of the homofunctional molecules, the dipole and quadrupole moments could be deduced. The corresponding theoretical quadrupole moment is approximated by the q_{zz} component calculated along the fitted quadrupole azimuthal angle. For the heterofunctional molecules, the present least-squares fitting procedure could only yield the product values of the dipole−dipole and dipole−quadrupole moments. The corresponding theoretical values calculated by the Hirshfeld partition method were also given in the tables for comparison. As shown in the tables, except for few cases, such as d_{PH2} of PP, $d_{SH} \times d_{PH2}$ and $d_{PH2} \times q_{SH}$ of SP, and $d_{PH2} \times q_{OH}$ of OP, in which the agreement between the theoretical and fitted values is only fair, the rest of the fitted and theoretical values are all in exellent agreement with each other.

The major discrepancy appears to come from the phosphino group. It has also been mentioned that, according to the average energy deviations as calculated in the global energy fitting procedure, the PP fitting is the worst. All of these suggest that the present potential function form is only a reasonably good approximation for the phosphino group. Additional refinement as suggested in the previous section is needed if one should demand a higher accuracy description for the phosphino compounds.

The transferability of the dipole and quadrupole moments of the functional groups among the molecules is very good. In general, the dipole moments are better than the quadrupole moments, and the theoretical values are better than the fitted ones in the transferability. For instance, the theoretical −OH dipole and quadrupole moments of methanediol are 1.43×10^{-18} esu cm and 4.48×10^{-26} esu cm^2; the theoretical −SH dipole and quadrupole moments of methanedithiol are 0.71×10^{-18} esu cm and 5.41×10^{-26} esu cm^2, respectively. Their corresponding products $d_{OH} \times d_{SH}$, $d_{OH} \times q_{SH}$, and $d_{SH} \times q_{OH}$ are 1.02×10^{-36} esu^2 cm^2, 7.74×10^{-44} esu^2 cm^3, and 3.18×10^{-44} esu^2 cm^3, respectively, which are in good agreement with the corresponding values of hydroxymethanethiol 1.05×10^{-36} esu^2 cm^2, 8.23×10^{-44} esu^2 cm^3, and 3.07×10^{-44} esu^2 cm^3, respectively. Note that the above theoretical dipole and quadrupole moments are the average values over the stable conformers. Owing to the polarization interaction and the possible mutual enhancement interaction between the two functional groups, as the conformation changes there are always some variations in the theoretical dipole and quadrupole moments. The standard percentage deviations of the theoretical values for the OH and NH_2 fragments are found to be around 10% and those for the SH and PH_2 fragments are 20%. Their implication on the present conformational potential representation shall be discussed in the following subsection.

The good agreement between the theoretical and fitted dipole and quadrupole moments of molecular fragments suggests that the electrostatic interaction energies between molecular fragments could be calculated directly from the atomic charge properties obtained from the ab initio method with the Hirshfeld partition. The intramolecular hydrogen bond energies could be quantitatively approximated by the electrostatic multipole interactions up to the quadrupole−quadrupole interaction term.

3c. Conformational Energy Decomposition and the Contribution of Intramolecular H-Bonding and Charge Delocalization Interaction to the Anomeric Effect. The general fitted function of eq 1 could be decomposed into two types of conformation interactions according to their dependence on the two torsional angles. The electrostatic interactions, which consist of the dipole−dipole, dipole−quadrupole, and quadrupole−quadrupole interactions, are simultaneously a function of the two internal rotations. The remaining interaction terms, V_0, V_a, and V_b, are dependent only on single rotation motion. The former is a through-space type of interaction and the latter a through-direct-bond type of interaction. The sum of the second type interactions has been named as the decoupled rotor potential. The dipole−dipole, dipole−quadrupole, and quadrupole−quadrupole terms constitute a quantitative representation of the through-space intramolecular potential between the functional groups. The decoupled rotor potential is a quantitative representation of both the steric effect and the components of the anomeric interactions of the functional groups with respect to their adjacent molecular fragments. In other words, the anomeric and exo-anomeric interactions of these molecules could be decomposed into two components: one is the component of electrostatic interactions through the space, the other is the interaction through the chemical bond. In the present study, the functional forms of the electrostatic interactions are rigorously defined. The through-direct-bond anomeric interactions can be calculated as the energy differences of the decoupled rotor potentials between the locally minimum conformations. The steric effect is expected to be responsible for the energy barriers at those conformations with either one or both of the two functional groups in eclipse positions to their adjacent molecular fragments. In the following discussion, the contributions of these various interactions to the final conformation potential are calculated from the fitted values of the individual decomposed potentials. Since a constant potential term was included in the decoupled rotor potential, in interpreting the decoupled rotor potential, only the relative conformational energies instead of their individual appearance energies are meaningful. For the electrostatic interaction terms, the zero energy is set at infinite interdipole distance.

Aminomethanephosphine as an Example. The global behavior of the decomposed conformational energies of aminomethanephosphine (NP) is shown in Figures 3 to 6, in which the dihedral angle of either one of the two functional groups is fixed at either 60° or 180° while that of the other functional group is varied

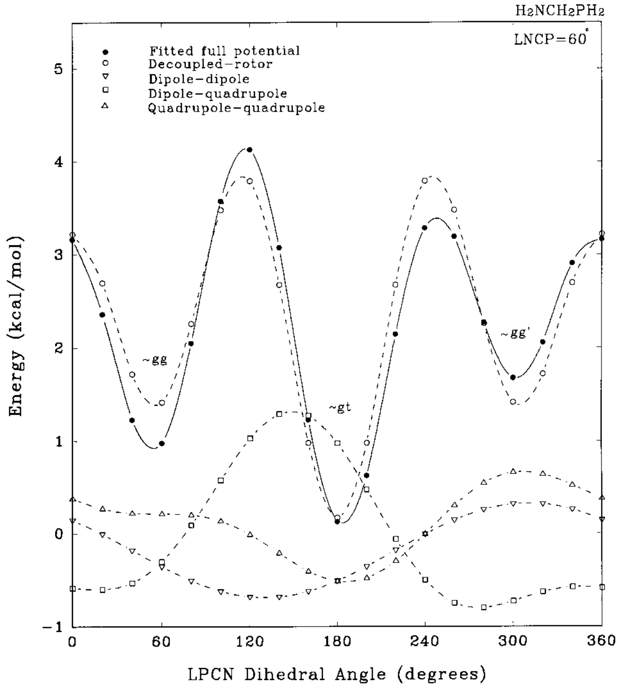


Figure 3. Decomposition of the conformational energy of aminomethanephosphine along the energy path (60,*x*) into the decoupled rotor, dipole−dipole, dipole−quadrupole, and quadrupole−quadrupole interaction energies.

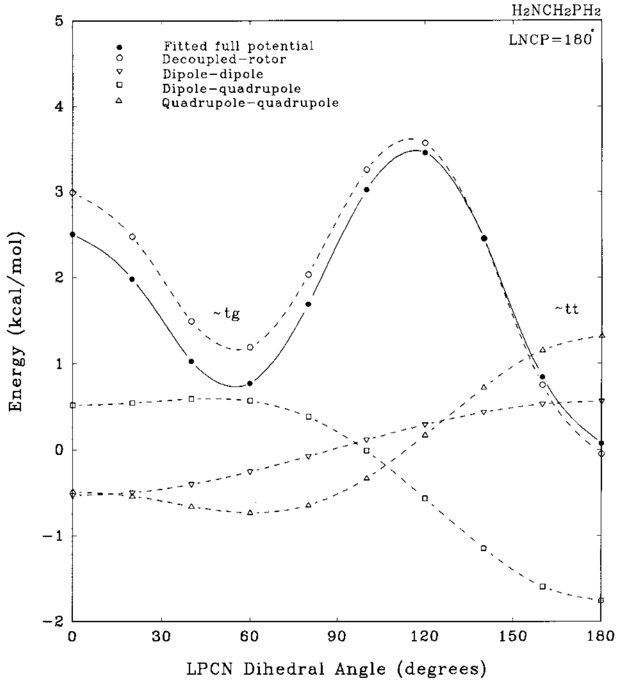


Figure 4. Decomposition of the conformational energy of aminomethanephosphine along the energy path (180,*x*) into the decoupled rotor, dipole−dipole, dipole−quadrupole, and quadrupole−quadrupole interaction energies.

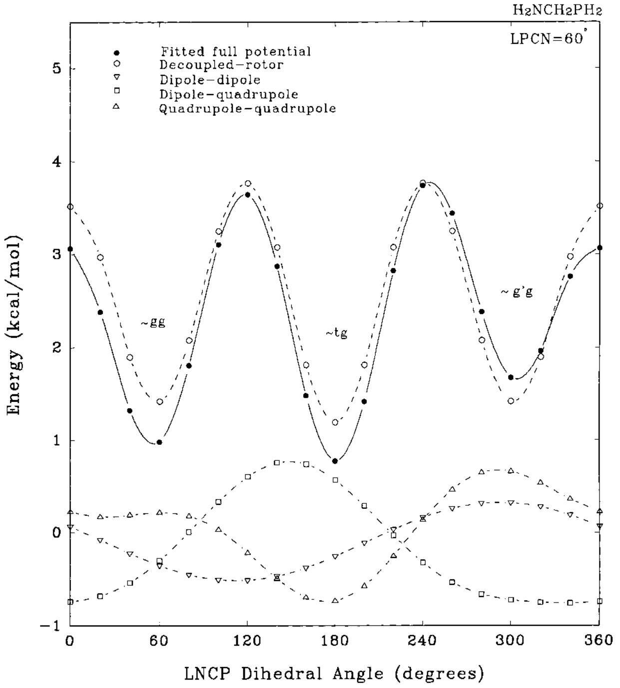


Figure 5. Decomposition of the conformational energy of aminomethanephosphine along the energy path (*x*,60) into the decoupled rotor, dipole−dipole, dipole−quadrupole, and quadrupole−quadrupole interaction energies.

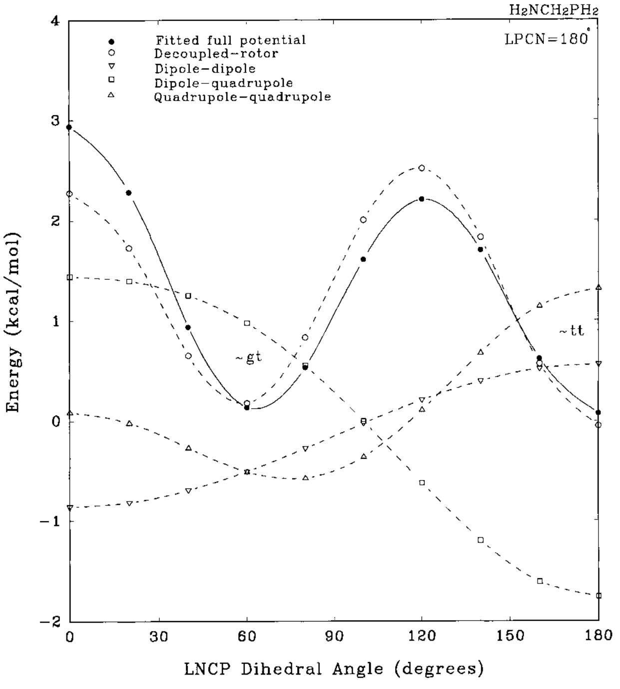


Figure 6. Decomposition of the conformational energy of aminomethanephosphine along the energy path (*x*,180) into the decoupled rotor, dipole−dipole, dipole−quadrupole, and quadrupole−quadrupole interaction energies.

over the full range of the angle. The local minima as shown in the figures are all close to the true local conformational minima as indicated in the figures. The energy difference between the fitted full potential and the decoupled rotor potential at each specified conformation is entirely due to the contribution of the intramolecular H-bonding.

Table 7 and part of Table 8 show the quantitative energy decomposition of NP at the potential barriers and energy minima. Depending on the conformation, the net electrostatic energy could be dominated by any combination of the three interaction forms: dd, dp, and qq interactions. For instance, in the case of the potential barriers, the net negative electrostatic energies of (0,60), (120,180), and (60,240) are mainly the result of the attractive interaction of dp. On the contrary, the net positive electrostatic energies of (0,180) and (60,120) are mainly the result of the repulsive interaction of dp. Finally, the small electrostatic contribution at the conformations of (120,60), (240,60), (60,0), and (180,120) is mainly the result of the near

TABLE 7: Decomposition of Some Barrier Energies of $H_2NCH_2PH_2$ (kcal/mol)

(H_2N,PH_2)	DR[a]	TE[b]	dd[c]	dq[c]	qq[c]
0,60	3.57	−0.45	0.06	−0.74	0.23
120,60	3.81	−0.12	−0.51	0.61	−0.22
240,60	3.79	−0.02	0.16	−0.32	0.14
0,180	2.32	0.66	−0.86	1.44	0.08
120,180	2.57	−0.30	0.21	−0.62	0.11
60,0	3.27	−0.05	0.15	−0.58	0.38
60,120	3.84	0.34	−0.68	1.03	−0.01
60,240	3.84	−0.50	0.00	−0.50	0.00
180,0	3.04	−0.49	−0.53	0.52	−0.48
180,120	3.61	−0.11	0.29	−0.57	0.17

[a] Relative decoupled rotor energies with respect to its most stable conformation energy listed in Table 8. [b] Total electrostatic energies. [c] Dipole−dipole (dd), dipole−quadrupole (dq), and quadrupole−quadrupole (qq) interaction energies.

cancellation among the above three interactions. For the case around the potential minima, all three components are contributing to the electrostatic energies. They almost cancel out with each other at the conformations of (180,180) and (60,180). The net negative electrostatic contribution at the (180,60) conformation is mainly the result of the attractive dd and qq interactions, and that at (60,60) is mainly the result of the attractive dd and dq interactions. On the other end, the increase of the potential energy by the electrostatic interaction at (60, −60) is mainly the result of the repulsive dd and qq interactions. Apparently, the conventional simplified picture of dipole−dipole interaction for the H-bonding is not adequate for global conformational energy description.

According to the general conclusion obtained in this lab previously, the relative decoupled rotor potential has been attributed to the contribution of the charge delocalization interaction between the lone-paired electrons of either one of the two electronegative atoms and its vicinal σ^* orbital.[17] The relative decoupled rotor energies of the five conformers of NP listed in Table 8 suggest that the $n(N) \rightarrow \sigma^*(CP)$ charge delocalization interaction is 0.23 kcal/mol and that of $n(P) \rightarrow \sigma^*(CN)$ is 1.24 kcal/mol. The conformational energy ordering of NP in terms of the relative decoupled rotor energies is consistent with the energy ordering of the stable local conformers shown in Table 1. This order is also in agreement with the statement of the generalized anomeric effect which would predict that the most stable conformer of NP is the tt conformer, and, depending on the relative orbital interaction strengths of the above two charge delocalization interactions, the next higher one would be either gt or tg conformer. Checking the contribution of the net electrostatic energies of NP in the table, one would find that the intramolecular H-bonding is exerting a reverse anomeric effect, i.e., the energy of the tt conformer is actually raised slightly higher, while the gt and tg conformers, especially the latter one, are actually lowered by the H-bonding. In other words, the anomeric effect originated from the charge delocalization interaction is compromised by the reverse anomeric effect of the intramolecular hydrogen bonding. As a consequence, the net anomeric interaction of NP becomes less pronounced as indicated by the relative conformational energies listed in Table 1. This phenomenon has been observed in the previous NO and NN systems and, additionally, also shows up in a number of the present molecular systems which are going to be discussed in the following subsection.

TABLE 8: Decomposition of the Conformational Energies of $H_nXCH_2YH_m$ (kcal/mol)

compd	X	Y	conformer	DR[a]	TE[b]	dd[c]	dq[c]	qq[c]
1	S	S	60,60	0.00	−0.15	−0.15	−0.53	0.53
			60,180	1.20	−0.15	−0.27	0.78	−0.66
			−60,60	0.00	1.28	0.47	−0.44	1.25
			180,180	2.40	0.91	0.51	−1.77	2.17
2	P	P	60,180	0.22	−0.31	0.00	0.02	−0.33
			180,180	0.00	0.66	0.00	−0.05	0.71
			−60,60	0.44	0.34	0.00	−0.01	0.35
			60,60	0.44	0.11	0.00	0.00	0.11
3	O	P	60,180	0.00	−0.10	0.42	−1.00	0.48
			180,180	0.17	−0.06	−0.98	2.11	−1.19
			−60,60	1.71	−0.64	−0.64	0.61	−0.61
			180,60	1.88	−0.09	0.27	−1.06	0.70
			60,60	1.71	0.20	0.30	0.09	−0.19
4	N	S	180,60	0.00	0.42	0.43	−0.76	0.75
			180,180	1.79	−0.31	−0.89	2.46	−1.88
			60,−60	2.92	−1.25	−1.05	1.04	−1.24
			60,180	4.71	−0.07	0.33	−0.58	0.18
			60,60	2.92	1.00	0.05	1.47	−0.52
5	N	P	180,180	0.00	0.12	0.56	−1.76	1.32
			60,180	0.23	−0.04	−0.51	0.98	−0.51
			180,60	1.24	−0.41	−0.25	0.57	−0.73
			60,60	1.47	−0.43	−0.35	−0.30	0.22
			60,−60	1.47	0.25	0.32	−0.73	0.66
6	O	S	60,60	0.00	−0.61	−0.38	−0.75	0.52
			−60,60	0.00	1.80	0.97	−0.40	1.23
			180,60	2.64	−0.10	−0.73	1.90	−1.27
			60,180	2.75	0.36	−0.54	1.35	−0.45
			180,180	5.40	0.20	1.05	−2.52	1.67
7	S	P	180,180	0.23	−0.58	−0.13	0.65	−1.10
			60,180	0.00	0.35	0.08	−0.37	0.64
			−60,60	0.56	−0.39	−0.11	0.22	−0.50
			60,60	0.56	−0.04	0.04	0.09	−0.17
			180,60	0.79	0.28	0.06	−0.32	0.54

[a] Relative decoupled rotor energies with respect to the most stable one listed in the table. [b] Total electrostatic energies. [c] Dipole−dipole (dd), dipole−quadrupole (dq), and quadrupole-quadrupole (qq) interaction energies.

Finally one needs to clarify the role of the electric induction contribution to the present conformation potential between the two functional groups. Its two lowest order terms are the charge-induced dipole and dipole-induced dipole interactions. There are two levels of consideration for these two interactions. First, since the major polarizability comes from the valence electrons, and for the present functional groups the main valence electrons are centered around the X and Y atoms, one could approximate the polarizability of the functional groups to be isotropic. According to the functional forms of the polarization interactions,[24] the electric induction contribution would mainly manifest in the decoupled rotor potential, in which the charge-induced dipole term is just a constant and the dipole-induced dipole interaction would contribute to the $\cos(2\omega_a)$ terms of eqs 2 and 3. In other words, the possible induction contribution, even if they were significant, would not affect the present results and conclusions on the electrostatic interaction. Second, one could estimate the upper bound of the dipole-induced dipole interaction by assuming that the standard percentage deviation of the theoretical dipole moment of the functional group comes entirely from the polarization effect. One finds that, depending on the magnitudes of the dipole moments, the possible maximum contribution to the decoupled rotor potential is in the range of 0.05 to 0.15 kcal/mol. In short, in the framework of the present analysis, the effect of the polarization interactions is not important.

General Results of $H_nXCH_2YH_m$. Table 8 shows the conformational energy decomposition of the seven systems calculated in this report. Along with the previous results of the OO, NN, and NO molecules, a total of 10 systems were obtained. In each case, the conformations are arranged according to the energy ordering of the local stable conformers listed in Table 1.

TABLE 9: Orbital Interaction Energies (kcal/mol)[a]

	σ^*_{C-O}	σ^*_{C-S}	σ^*_{C-N}	σ^*_{C-P}
n_N	3.30(2.81)	2.92(2.74)	1.20(1.00)	0.23(0.34)
n_O	2.90(2.81)	2.64(2.72)	0.78(0.76)	0.17(0.19)
n_S	2.75(2.72)	1.20(1.21)	1.79(1.81)	0.23(0.17)
n_P	1.71(1.81)	0.56(0.55)	1.24(1.26)	0.22(0.13)

[a] The numbers in parentheses are electrostatic energy corrected values.

According to the predictions of the anomeric effect, the most stable conformer for the compounds listed in Table 1 would be gg or gg′ (SS), tt (PP), gt (OP), tg (NS), tt (NP), gg or g′g (OS), and gt (SP). As shown in the table, except for the PP and SP molecules, these predictions are in agreement with the results obtained through the relative MP2 conformational energies. Traditionally, the extra stability of these conformers was then qualitatively attributed to the contribution of the $n(X) \rightarrow \sigma^*(CY)$ charge delocalization interaction. For the special case of PP and SP, the gt and tt instead of the tt and gt conformers are the most stable ones. The conventional interpretation would suggest that, for these two specific molecules, either there is no anomeric effect or the reverse anomeric effect that is due to the intramolecular H-bonding is responsible for the observed abnormality. Apparently, even for these simplest prototype molecules, the conventional interpretation of the anomeric effect is not satisfactory. A more comprehensive treatment is needed.

As shown in Table 8, for all of the molecules considered, the conformations with the lowest decoupled rotor energy are in agreement with those predicted by the anomeric effect. The relative decoupled rotor energies among the conformers have been attributed to the $n(X) \rightarrow \sigma^*(CY)$ charge delocalization interaction. Their values are summarized in Table 9. Since the decoupled rotor potentials still contain some minor electrostatic components through the interactions between net electric charge of the molecule fragment, say $-$XH, and the dipole and quadrupole moments of the $-$YH fragment, the values in the brackets are the orbital interaction energies after the electrostatic corrections. Except for the $n(N) \rightarrow \sigma^*(CO)$ case, the magnitudes of the electrostatic corrections are all within the energy uncertainty of the present energy decomposition scheme. In other words, on the basis of either the decoupled rotor energies or the electrostatic corrected values, one would reach essentially the same general orbital interaction picture among these molecules. As a note, in the present discussion, the relative decoupled rotor energies and the orbital interaction energies are treated as equivalent terms. For the decomposition of the conformation energy, the values of the decoupled rotor energies shall be adapted, and for comparison of the relative orbital interaction energies, the electrostatic corrected values shall be adapted.

On the side of the electrostatic contributions to the conformational energies, two opposite effects could be found: one is the enhancement of the anomeric effect in the SS and OS molecules; another is the reverse anomeric effect in the PP, NS, NP, OP, and SP systems. For the former two molecules, their most stable conformers are further stabilized by the intramolecular H-bonding, in which, depending on the molecules, the dipole$-$dipole and/or dipole$-$quadrupole interactions are playing important roles. In the latter case, for the NS, NP, and OP molecules, the electrostatic energies are less important than those of the orbital interactions such that the most stable conformers are still in agreement with the predictions of the conventional anomeric effect. The consequence is that their relative conformation stabilities owing to the decoupled rotor energies are compromised by the reverse anomeric effect of the electrostatic interactions. Finally, for the remaining PP and SP molecules, the reverse anomeric effect of the electrostatic interactions outweighs the stabilization of the orbital interaction such that the most stable conformers are either determined mainly by the qq interaction for the PP molecule or the dq and qq interactions for the SP molecule.

In the framework of the orbital interaction theory, the stabilization energy of the two electron$-$two orbital interaction between an occupied donor orbital and an empty acceptor orbital is inversely proportional to the energy difference between the interacting orbitals.[25,26] It is generally accepted that the effectiveness of the donor orbitals of lone-pair electrons follows the order $n_S > n_P \approx n_N > n_O$ and the order of the acceptor orbitals is $\sigma^*(CS) > \sigma^*(CP) > \sigma^*(CO) > \sigma^*(CN)$.[1a,1c,25,27] As shown in Table 9, for the O, N, S, and P elements, the above-mentioned rules are only partially correct. More specifically, it holds only for the elements in the same periodic row, i.e., $n_S > n_P$ and $n_N \geq n_O$ for the donor orbitals of lone-paired electrons, and $\sigma^*(CS) > \sigma^*(CP)$ and $\sigma^*(CO) > \sigma^*(CN)$ for the acceptor orbitals. Going over different rows of elements, one could only obtain some general trends in which minor exceptions are always present. For instances, for the $\sigma^*(CO)$, $\sigma^*(CS)$, and $\sigma^*(CP)$ acceptor orbitals, the effectiveness of the donor orbitals is in the order of $n_N \geq n_O > n_S > n_P$; while for the $\sigma^*(CN)$ orbital, they are in the order of $n_S > n_P > n_N > n_O$. On the other end, for the n_N and n_O donor orbitals, the effectiveness of the acceptor orbitals is in the order of $\sigma^*(CO) > \sigma^*(CS) > \sigma^*(CN) > \sigma^*(CP)$; while for the n_S and n_P donor orbitals, the order becomes $\sigma^*(CO) > \sigma^*(CN) > \sigma^*(CS) > \sigma^*(CP)$. Apparently, the generally accepted rules are not universally applicable as one goes over different periodic elements. In short, present energy decomposition analysis provides a quantitative guideline for the above conventionally accepted rules.

For a given anomeric molecule, it has been generally suggested that the correlation between the bond length and the conformation of the atom with lone-pair electrons is the consequence of the charge delocalization interaction.[2,28−30] Along this line, more recently, it also has been established that the decoupled rotor potential is well correlated with the length of the chemical bond that is involved in the charge delocalization interaction.[17] In this report, we went one step further to examine the correlation between the bond lengths and the orbital interaction energies among the 10 compounds. For the general structure $H_nXCH_2YH_m$, one may fix the $-YH_m$ fragment in the off-orbital interaction conformation and vary the H_nX fragment over the four elements. Four C$-$X bond lengths were then calculated in the $n(X) \rightarrow \sigma^*(CY)$ orbital interaction conformations. A total of four correlation relations were obtained and are shown in Figure 7. The data points are represented by the symbol (X,Y), in which the first element X indicates that the X$-$C bond lengths are calculated and their corresponding orbital interaction energies of $n(X) \rightarrow \sigma^*(CY)$ are adapted directly from Table 9, and the second element Y indicates that Y is varied over the four elements considered in this report. Each data set was then fitted with a linear function. The linear correlation coefficients of the four data sets are 0.88 (O,Y), 0.96 (N,Y), 0.96 (S,Y), and 0.90 (P,Y), respectively. Clearly, the linear relations among the compounds of the same series are reasonably good and can serve as additional support for the general orbital interaction picture as discussed in this section.

3d. A General Discussion on Some Related Works in the Literature. As mentioned previously, the anomeric and exo-anomeric effects of the second and third row elements have been a subject of interest for some time.[1] Based on the present

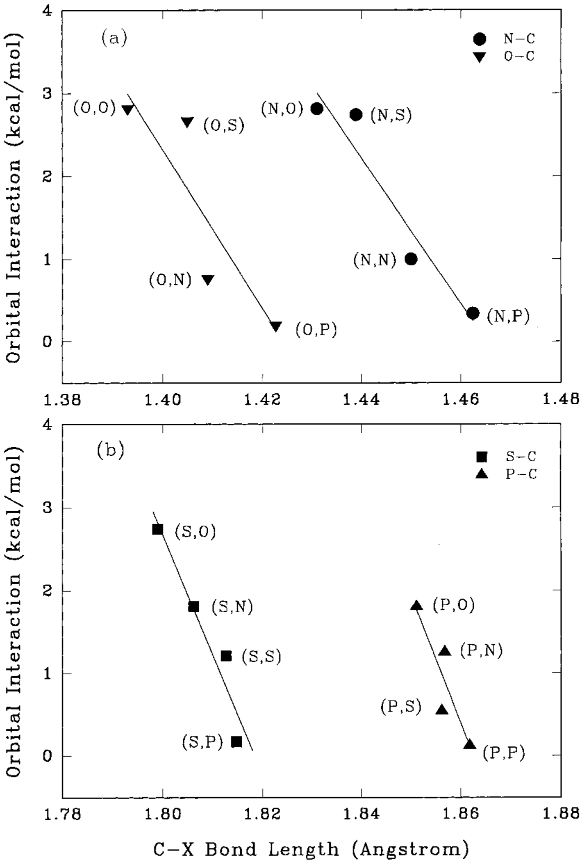


Figure 7. Linear relationships between the orbital interaction energies of *n*(X) → σ*(CY) and the C−X bond lengths as Y varies over the four elements O, S, N, and P of the (X,Y) compounds.

energy decomposition scheme, studies in the literature, which are related to the present molecular systems, shall be discussed in this subsection.

The electrostatic model for the anomeric effect was first proposed by Edward.[31] Subsequent observations on the relation between the molecular dipole moment and the molecular conformations,[29] the experimental evidences of the solvent effect,[32] and the substitution effect of the anomeric atoms on the anomeric energies[33] suggest that the electrostatic interactions play an important role in the anomeric effect. Nevertheless, as mentioned previously, the relative importance between the electrostatic interaction and the charge delocalization interaction in the anomeric effect is still not convincingly resolved.[18] The present decomposition scheme clearly shows the importance of the reverse anomeric effect manifested by the electrostatic interaction in the nitrogen-containing anomeric molecules as discussed in the literature. It clarifies the role that the electrostatic interactions play in the anomeric effect in the second- and third-row anomeric molecules.

Salzner and Schleyer have analyzed the anomeric effect of the OO and SS molecules in the framework of NBO analysis.[13] They concluded that the contributions of the hyperconjugative interactions to the anomeric effect in SS are larger than that in OO, while the nonhyperconjugative (e.g., steric and electrostatic) contributions are in the reverse order such that the net anomeric effect in the SS molecule is smaller than that in the OO molecule. In contrast, the present analysis suggests that both the orbital interactions and electrostatic interactions contribute positively to the anomeric effect, except that they are weaker in the SS system. There is no simple one-to-one correspondence between the energy terms of the NBO method and the present energy decomposition scheme. Nevertheless, it is interesting to know the differences between these two lines of argument.

The anomeric interactions of the O−C−N, O−C−O, and O−C−S systems have been studied theoretically by Tvaroška and Carver through the molecules 2-methylamino-tetrahydropyran, 2-methoxytetrahydropyran, and 2-methylthiotetrahydropyran.[34] They concluded that the anomeric effect decreases in the order of methoxy, thiomethyl, and methylamino groups, and the exo-anomeric effect decreases according to the order of methoxy, methylamino, and thiomethyl groups.[34] Because the intramolecular electrostatic interactions in these cyclic systems are weaker than those of the corresponding methane counterparts, so are their contributions to the anomeric and exo-anomeric effects. For these cyclic systems, it is expected that the anomeric and exo-anomeric effects are mainly determined by the orbital interaction energies. The above group ordering of the anomeric effect is then mainly a manifestation of the ordering of the orbital interaction energies of *n*(O) → σ*(CO), *n*(O) → σ*(CS), and *n*(O) → σ*(CN), while the group ordering of the exo-anomeric effect corresponds to the ordering of the orbital interaction energies of *n*(O) → σ*(CO), *n*(N) → σ*(CO), and *n*(S) → σ*(CO). These relative anomeric and exo-anomeric strengths are in good agreement with the relative order of the orbital interaction energies listed in Table 9. For a more quantitative comparison, one would need to take the steric interactions of the tetrahydropyran system into account. Taking the empirical procedure adapted by the above authors and approximating their steric interaction energies to be mainly energetic, one could obtain the anomeric energies of the methoxy, methylthiol, and methylamino groups of these cyclic systems to be 3.0, 1.5, and 0.0 kcal/mol, respectively.[34,35] These values are reasonably close to the predicted orbital interaction energies of 2.81, 2.66, and 0.76 kcal/mol obtained in this study. For a more quantitative comparison, one would need more refined calculations on the tetrahydropyran systems, which include higher level energy calculations beyond the Hartree−Fock level, a more detailed analysis of the intramolecular electrostatic interactions, and a better account of the steric interaction energies.

Experimentally, the conformational behaviors of the O−C−O, O−C−S, S−C−S, O−C−N, and S−C−N systems have been studied by a number of research groups through the molecular systems of 2-methoxytetrahydropyran, 2-methoxytetrahydrothiopyran, 2-ethylthiotetra-hydrothiopyran, 2-methylthiol-1,3-dithiane, 2-methylaminotetrahydropyran, and 2-dimethylamino-1,3-dithiane in a number of solvents.[1c,36−40] These studies suggested that for the first four compounds, the anomeric effect is in operation; for the fifth compound, the steric hindrance in the axial isomer dominate over the anomeric effect; and, for the sixth one, the antiperiplanr *n*(N) → σ*(CS) interaction of the equatorial conformer is more important than the antiperiplanar *n*(S) → σ*(CN) interaction of the axial isomer. These conclusions are in line with the general trend of the corresponding orbital interaction energies listed in Table 9, i.e., the orbital interaction energies of *n*(O) → σ*(CO), *n*(S) → σ*(CO), and *n*(S) → σ*(CS) are comparatively in the high value side; the orbital interaction energy of *n*(O) → σ*(CN) is only 0.76 kcal/mol; and the *n*(N) → σ*(CS) orbital energy is larger than that of *n*(S) → σ*(CN) by 0.93 kcal/mol. Nevertheless, for a quantitative comparison, detailed energy estimations of the solvent effect and the steric interactions for the conformers of these cyclic systems are needed. For the S−C−P system, Graczyk and Mikolajczyk studied the conformational behavior of 2-(disubstituted phosphino)-1,3-dithianes in polar solvent and concluded that $n(P) \rightarrow \sigma^*(CS)$ orbital interaction is not important for the S−C−P anomeric interactions in the axial conformer.[41] In the present study, the $n(P) \rightarrow \sigma^*(CS)$ orbital interaction energy is determined to be 0.55 kcal/mol. Apparently, the anomeric energy is too small to dominate the energetics of the bulky disubstituted phosphino group. The present result is also in line with the experimental observation.

In a critical review of the reverse anomeric effect, Perrin suggested that for the protonated compounds ($Y-CH_2-X^+$ ($Y= H_2N$ or HO, $X= NH_3$, OH_2, or FH)) the reverse anomeric effect could be accounted for by the H-bonding, and for the compounds involving quaternary nitrogen, such as the protonated N−(glucopyranosyl)imidazole, the origin of the reverse anomeric effect was electrostatic interaction in nature.[42] The present energy decomposition analysis on the neutral molecules also suggests that the electrostatic interactions are operating in the reverse anomeric effect mode for the compounds containing nitrogen and/or phosphor. The present results are in agreement with the physical picture of the reverse anomeric effect as suggested by Perrin. For a further quantitative comparison, a global conformational analysis on the protonated systems would be needed.

4. Conclusions

In this work, the global ab initio conformational energies of the title compounds were obtained. A general analytic potential form, which includes the through-space potentials of the electric dipole−dipole, dipole−quadrupole, and quadrupole−quadrupole interactions, and through-direct-bond decoupled-rotor potentials were found to be adequate in representing these ab initio global conformational potentials. The fitted local dipole and quadrupole moments of the functional groups are in good agreement with the corresponding ab initio values calculated by the Hirshfeld partition. The energy decomposition analysis of the global conformation potential into the decoupled rotor potential and the electrostatic interaction potentials suggests that they are equally important in the manifestation of the anomeric effect for these molecules.

Sixteen orbital interaction energies of $n \rightarrow \sigma^*$ involving in the title compounds were obtained. These energies, along with the electrostatic energies, provided a unified picture for the anomeric and exo-anomeric effect of the related molecular systems reported in the literature and also could be used as a guideline for further experiments on new molecular systems. On the basis of the present results, the related works in the literature were reviewed and discussed.

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Supporting Information Available: Four tables that include the fitted and structural parameters of aminomethanephosphine, hydroxymethanephosphine, mercaptomethanephosphine, and hydroxymethanethiol. This material is available free of charge via the Internet at http://pubs.acs.org.

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