9. A PCILO Study of Conformation and Internal Rotation in Mono-substituted Benzenes

by **Jürgen Gerhards**[1]), **Tae-Kyu Ha**[2]) and **Xavier Perlia**[1])

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Summary

The effect of *Kékulé* representation and hybrid function of O-atoms in the PCILO-CNDO framework of conformation and internal rotation in mono-substituted benzenes Ph-X (X = NH_2, OH, OCH_3, CH_3, CHO, NO_2) is studied. Three variational criteria for the choice of the appropriate third-order energy, proposed to symmetrize the PCILO results, are critically examined in relation with the height of rotational barrier in these molecules. The study shows that, in all cases, the most stable conformation is qualitatively correct predicted by the PCILO method. Since the barrier to internal rotation in the studied aromatic systems arises predominantly from delocalization effect, it is proposed to employ the arithmetic mean of the third-order energy of the two *Kékulé* structures. In molecules, in which the third-order energy between the two *Kékulé* structures is larger than 2 kcal/mol, however, the lower third-order energy representation alone seems to be appropriate. In phenol and anisole the sp^3-hybridization type of the O-atoms offers better values of rotational barrier, whereas in the sp^2-type the delocalization is overestimated in the planar conformation.

1. Introduction. – The studies of the relationship between the molecular structure of active drugs and their biological effect are based on the assumption that the specific interaction between the active drug and its receptor can be explained and described in the same terms as those for chemical reactions and interactions [1]. The required informations about molecular reactivity parameters can be obtained – beside experimental methods – from quantum-chemical calculations [2] [3]. In the field of conformational analysis of polyatomic molecules like drugs the PCILO method *(perturbation configuration interaction using localized orbitals)* is extensively used because of its speed and recognized successes [4-6]. A general description

[1]) Pharmazeutisches Institut der Eidgenössischen Technischen Hochschule Zürich, CH-8092 Zürich.
[2]) Laboratorium für Physikalische Chemie der Eidgenössischen Technischen Hochschule Zürich, *CH-8092 Zürich.*

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of the main features of this method, first introduced by *Diner et al.* [7], has been given in a recent review [8].

Through the localization of bonding orbitals in the PCILO framework different chemical formulae are possible for the same configuration. Substituents can break the energetical equivalence between the two *Kékulé* representations of benzenes and heteroaromatic systems. The same holds for some functional groups (carboxylate, nitro, phosphate *etc.*). To symmetrize the results within the PCILO method three variational criteria were proposed previously: *a*) choice of the representation giving the lower zeroth-order energy (E_0-criterion) [7]; *b*) choice of the representation giving the lower third-order energy (E_3-criterion) [9]; *c*) arithmetical mean between the two third-order energies (A + B/2-criterion) [9].

Since most of the previously reported applications of the PCILO method are focused on qualitative features, the handling of the cited criteria are not well documented. In 1-acetyl-2-(4-methoxybenzyl)-3-pyrroline (= 1-(*N*-Acetyl-3-pyrrolin-2-yl)methyl-4-methoxybenzol) [10] the energetical difference between the two *Kékulé* structures was calculated as 0.6 kcal/mol and in benzylfluoride [11] it amounted to 1.2 kcal/mol. To recover the symmetry in the former molecule the E_0-criterion and in the latter molecule the (A + B/2)-criterion was used.

Another study [12] shows that, depending on the *cis*- or *trans*-position of the carbonyl group in nicotinamide, benzaldehyde and benzoic acid to the double bond arrangement of the two *Kékulé* structures, a different potential function of internal rotation was obtained. In a study of phenethylamine [9] it is shown that in the free base of phenethylamine the three criteria give conformational results in satisfactory accord, while in the protonated species the shape of the conformational surface showed some differences. The position of the minima does not change substantially. Compared with *ab initio* STO-3G calculations the best fit is obtained with the E_0-criterion. The three versions give even quite different pictures of the rotational surface of zwitter-ionic glycine [13]. Passing from the E_0- to the E_3- and then to the (A + B/2)-criterion the potential surface becomes gradually smoother, whereas the (A + B/2)-criterion can grouped together with *ab initio* STO-3G and CNDO/2 results giving fairly similar conformational maps. In the conformational analysis of benzylideneaniline and azobenzene [14] it seems not reasonable, to consider only one *Kékulé* structure in the calculation. The arithmetic mean value is in agreement with experimental determinations of the most stable conformation.

Another point of interest in the PCILO method is the hybridization type of O-atom adjoined to aromatic systems. The two possible descriptions of the localized orbitals of the lone-pair electrons of the O-atom in diphenyl ether by the canonical hybrid function sp^2 or sp^3 are found to be not equivalent [15].

Since the justification of the choice of one of the cited energy-criteria relies upon the comparison of the computed results with experimental data, we undertook a conformational analysis of monosubstituted benzenes, Ph-X (X = NH_2, OH, OCH_3, CH_3, CHO, NO_2), for which the most stable conformations as well as barriers to internal rotation are well-known from experiments. Furthermore, these compounds are important constituents of larger molecules of pharmacological interest, often used in drug design for substituent-variated properties of reaction centers.

2. Results and discussion. – All calculations were performed on a *CDC* computer at the Computer Center ETH-Zürich using the *QCPE 221* program [16]. The polarities of bonds were optimized for all conformations. The employed geometries are given in *Table 1*. The results of the PCILO calculations are listed in *Table 2* and compared with those obtained from experimental and other theoretical studies. The *Kékulé* structures are designated by A or B and their mean value of the third-order energies as (A+B/2). The canonical hybrid functions for the O-atom sp^3 and sp^2 are termed σ, π, respectively. The computational results will be discussed in the following separatly for each molecule, in detail.

a) *Toluene.* By experimental studies a very low sixfold-barrier of 14 cal/mol hindering the internal rotation of the methyl group has been found [23] [24]. This type of potential function can be considered as the cancellation of two identical potential functions orthogonal to each other, arising from the rotation of the methyl group with a threefold symmetry against the twofold symmetric frame of the phenyl system [60].

Interestingly, the PCILO calculation confirms this view exactly. *Kékulé* structures A and B *(Fig. 1)* show separatly a threefold potential function 180° out-of-plane with a height of barrier $V_3 = 1.18$ kcal/mol *(Fig. 2)*. Superposing these two *Kékulé* structures by the mean value of their third-order energies offers a correct

Table 1. *Molecular geometries employed for PCILO calculations*

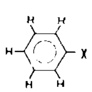
Molecule	Angles (degree)		Distances (A)	
	all CCC all CCH	120.0 [17] 120.0 [17]	all C–C all C–H	1.400 [17] 1.080 [17]
Ar–N(H)H (planar)	CNH HNH	120.0 120.0	C–N N–H	1.402 [18] 1.001 [18]
Ar–O–H (planar)	CCO COH	122.2 [19] 109.0 [19]	C–O O–H	1.364 [19] 0.956 [19]
Ar–O–CH_3 (planar)	CCO COC all OCH	124.4 [20] 118.1 [20] 109.47 [17]	C_{Ar}–O O–C all C–H	1.356 [20] 1.435 [20] 1.090 [17]
Ar–C(=O)H	CCC CCO CCH	120.0 120.0 120.0	C–C C–O C–H	1.460 [21] 1.220 [21] 1.090 [21]
Ar–$N^{(+)}$(=O)$O^{(-)}$	CCN both CNO	120.0 118.0 [22]	C–N N–O	1.476 [22] 1.220 [22]
Ar–CH_3	CCC CCH	120.0 111.1 [23]	C–C C–H	1.510 [23] 1.087 [23]

Table 2. *Comparison of rotational barriers of mono-substituted benzenes computed by PCILO calculations with those obtained by experimental and other theoretical methods*

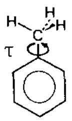
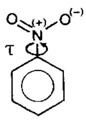
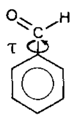
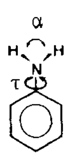
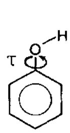
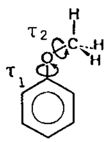
Molecule	Kind of motion	PCILO (this work)	Experimental data	Other theoretical methods
	Rotation τ	A $V_3 = 1.174$ B $V_3 = 1.173$ (A+B/2) $V_6 = 0.012$	$V_6 = 0.014$ [23] [24]	*ab initio* STO-3G < 0.006 [25]
	Rotation τ	A $V_2 = 3.180$ B $V_2 = 2.305$ (A+B/2) $V_2 = 2.742$	$V_2 = 2.8 - 3.0$ {3.0 [26], 2.78 [27]}	MINDO/3 6.9 ($\tau = 90°$) [28] MNDO 4.9 ($\tau = 90°$) [28] *ab initio* STO-3G 5.74 ($\tau = 0°$) [25]
	Rotation τ	A $V_2 = 1.637$ B $V_2 = 4.045$ (A+B/2) $V_2 = 2.841$	$V_2 = 4.7 - 4.9$ {4.66 [30], 4.9 [31]}	CNDO/2 1.1 ($\tau = 90°$) [32] CNDO/2 1.2 ($\tau = 90°$) [33] CNDO/2 (STO-3G optimized) 1.1 ($\tau = 0°$) [33] PCILO 2.45 ($\tau = 0°$) [33] PCILO 3.30 ($\tau = 0°$) [34] PCILO *Kékulé* A 1.29 ($\tau = 0°$) [13] *Kékulé* B 3.30 ($\tau = 0°$) [13] *ab initio* STO-3G 6.60 ($\tau = 0°$) [25] *ab initio* STO-3G 6.56 ($\tau = 0°$) [33] *ab initio* STO-3G 5.84 ($\tau = 0°$) [33] (partially optimized)
	Barrier to inversion	A = B 7.303	1.3 – 1.6 {1.3 [35], 1.61 [36], 1.50 [37]} {$\alpha = 37.5°$ [18], 42° [35], 46° [36]}	CNDO/2 6.4 [39] CNDO/2 7.6 ($\alpha = 54°$) [40] CNDO/2 5.97 ($\alpha = 54°$) [41] INDO 1.2 ($\alpha = 39°$) [40] *ab initio* STO-3G 2.7 ($\alpha = 48°$) [25] STO-3G 4.3 ($\alpha = 51°$) [42] STO-(1+1+1)G 1.1 ($\alpha = 38°$) [42] [5.2/2]DZ 0.9 ($\alpha = 39°$) [42]
	Rotation τ	$\alpha = 0°$ A 11.47 B 11.47 (A+B/2) 11.47 $\alpha = 55°$ A 5.816 B 7.929 (A+B/2) 6.873	3.54 [38]	CNDO/2 $\alpha = 0°$ 16.06 [41] $\alpha = 54°$ 4.30 [41] INDO $\alpha = 0°$ 10.3 [40] $\alpha = 39.4°$ 7.5 [40] *ab initio* STO-3G $\alpha = 0°$ 10.7 [43]
	Rotation τ	σA 3.305 σB 2.814 σ(A+B/2) 3.060 πA 5.267 πB 4.612 π(A+B/2) 4.940	3.4 {3.29 [44], 3.26 [45], 3.36 [19], 3.47 [46], 3.56 [47]}	CNDO/2 2.31 ($\tau = 0°$) [48] CNDO/2 2.76 ($\tau = 0°$) [49] *ab initio* STO-3G 5.15 ($\tau = 0°$) [25] STO-3G 4.71 ($\tau = 0°$) [50] STO-3G 4.08 ($\tau = 0°$) [51] (INDO-optimized)

Table 2 (continued)

Molecule	Kind of motion	PCILO (this work)		Experimental data	Other theoretical methods	
	Rotation τ_1	σA	2.751	not certain	CNDO/2	1.76 ($\tau_1 = 0°$) [54]
		σB	1.724	{3.61 [52],	CNDO/2	1.00 ($\tau_1 = 0°$) [49]
		σ(A + B/2)	2.238	> 1.1 [53]}	INDO	($\tau_1 = 90°$) [50]
		πA	5.030		MINDO/3	1.28 ($\tau_1 = 0°$) [55]
		πB	3.550		*ab initio* STO-3G	0.06 ($\tau_1 = 0°$) [25, 51, 56]
		π(A + B/2)	4.290			
					ab initio STO-3G	0.94 ($\tau_1 = 0°$) [50]
					ab initio STO-3G	1.34 ($\tau_1 = 0°$) [50]
	Rotation τ_2	with $\tau_1 = 0°$		1.8 – 2.8	INDO $\tau_1 = 20°$	4.02 [59]
		σA	3.403	{1.79 [57],	$\tau_1 = 90°$	1.05 [59]
		σB	3.301	1.79 [58],		
		σ(A + B/2)	3.352	2.8 [59]}		
		πA	3.600			
		πB	3.201			
		π(A + B/2)	3.401			

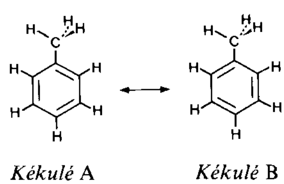


Fig. 1. *Designation of the* Kékulé *structures of toluene*

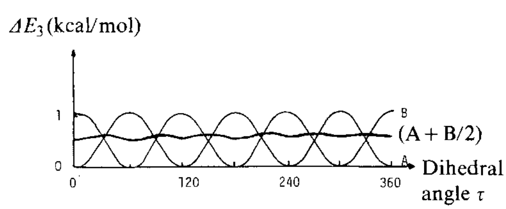
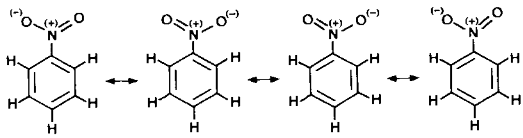


Fig. 2. *Rotation of the methyl group in toluene*

sixfold potential function with a barrier of $V_6 = 12$ cal/mol. The most stable conformation is found to be that one with one H-atom in the plane of the phenyl system.

b) *Nitrobenzene.* Supported by the experimentally determined planar structure of nitrobenzene in its ground state [26] [29] it can be assumed that the N-atom enters into chemical bonding in an sp^2-hybridized state. Three of the sp^2-orbitals form planar σ-bonds with the O-atoms and the ring C-atom. The remaining N-p-orbital forms a bond with one of the O-atoms, in which the ring electrons are largely delocalized *(Fig. 3).*

Assuming a symmetric nitro group the *Kékulé* structures A, A_1, B and B_1 can be reduced to two different arrangements with respect to the substituent ($A = B_1$ and $B = A_1$). Therefore, the arithmetical mean of the two *Kékulé* structures seems to describe the system *a priori* in an appropriate manner.



Kékulé A_1 *Kékulé* A *Kékulé* B *Kékulé* B_1

Fig. 3. *Designation of the* Kékulé *structures of nitrobenzene*

In the first definition the negative-charged O-atom is considered to be *sp*-hybridized. Within this description an unrealistically large dipole moment of 41.2 D is calculated compared to the experimental value of 4.22 D [61]. Evident by the poor convergence of the CI-terms *(Table 3),* especially the very large delocalized single excitation, the degree of delocalization in the system becomes too large to be treated as perturbation in the localized picture of the PCILO framework [62].

In the second definition the negative-charged O-atom is described as sp^3-hybridized, which leads to a more reasonable dipole moment of 5.55 D and a better convergence in the CI-terms. In spite of the ambiguity of the sp^3-hybridization of the negative charged O-atom the conformational results of the PCILO calculations are in good agreement with experiment *(Table 2).* In both *Kékulé* structures the planar conformation is found to be the most stable one and a twofold barrier is hindering the internal rotation of the nitro group. The third-order energies of the two *Kékulé* structures in the planar conformation are different by 0.88 kcal/mol, favouring the *Kékulé* structure A. In the orthogonal conformation the two representations are equivalent. Both the E_0- and the E_3-criteria lead to the *Kékulé* structure A as the lower one in energy. Compared with the experimentally determined rotational barrier of 2.8–3.0 kcal/mol [26] [27] the *Kékulé* structure A amounts to a better predicted height of barrier (3.18 kcal/mol) than the *Kékulé* structure B (2.31 kcal/mol). The best agreement with experiment is, however, obtainable from the arithmetical mean value of the two representations (2.74 kcal/mol) *(Table 2).*

Table 3. *PCILO energy contributions of nitrobenzene* (kcal/mol)

Dihedral angle τ	$\tau = 0°$			$\tau = 90°$
Hybridization type of O-atom	*sp*	sp^3	sp^3	sp^3
Kékulé structure	A	A	B	A = B
Nuclear repulsion energy	131939.47	131939.47	131939.47	131416.46
E_0 (zeroth-order energy)	−59002.281	−59076.882	−59075.768	−59076.298
Delocalization energy	−641.406	−367.990	−368.521	−364.493
Intra-bond correlation energy	−127.626	−127.123	−127.325	−127.287
Inter-bond correlation energy	−169.660	−169.682	−171.750	−169.423
E_2 (second-order energy correction)	−938.692	−664.795	−667.596	−661.203
$E_0 + E_2$	−59940.973	−59741.677	−59743.364	−59737.501
Delocal. 2 bonds correl. interaction[a])	−11.333	−11.344	−12.066	−10.924
1 Bond correl. 2 bond correl. interaction	76.805	76.904	78.556	77.135
Delocal. delocal. interaction	−35.176	−74.291	−76.728	−76.797
2 Bond correl. 2 bond correl. interaction	52.925	52.953	57.023	53.812
E_3 (third-order energy correction)	83.221	44.222	46.785	43.226
$E_0 + E_2 + E_3$	−59857.752	−59697.455	−59696.579	−59694.275

[a]) Delocal. stands for 'delocalization' and correl. for 'correlation'.

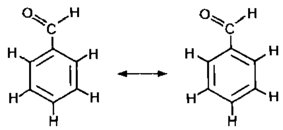


Fig. 4. *Designation of the* Kékulé *structures of benzaldehyde*

This PCILO result may be contrasted to previous MINDO/3 and MNDO results, which predict the orthogonal conformation to be the most stable conformation [28]. As for the barrier height, an *ab initio* calculation with STO-3G basis set [25] gave 5.44 kcal/mol, overestimating the experimental value appreciably.

c) *Benzaldehyde.* Benzaldehyde *(Fig. 4)* is known to be planar in the ground state and has a twofold barrier with a height of 4.7–4.9 kcal/mol [30] [31]. This planar conformation is also confirmed from previous and the present PCILO studies as the most stable one *(Table 2)*, though the calculated barrier seems to be sensitive to the employed geometry.

In the present study, the variational criteria for the choice of the appropriate energy value lead to different *Kékulé* structures *(Table 4)* (E_0-criterion→*Kékulé* A, E_3-criterion→*Kékulé* B). A comparison between the values of the two *Kékulé* structures and experimental data shows that the rotational barrier obtained from *Kékulé* structure B gives better agreement with experiment *(Table 2)*. In spite of a large energy difference between both *Kékulé* structures in the planar conformation ($\Delta E_3^{AB} = 2.4$ kcal/mol), it may be concluded that, in the localized picture of the PCILO method, both *Kékulé* structures have a different weight in the planar conformation, the *Kékulé* structure B being the dominant form. In view of this, it seems not advisable to choose the (A+B/2)-criterion for the description of the internal rotation in benzaldehyde. In the orthogonal state the two *Kékulé* structures are found to be equivalent, as expected.

Compared with other theoretical studies on benzaldehyde, the PCILO method gives a better qualitative picture of the rotational behaviour. The failure of the

Table 4. *PCILO energy contributions of benzaldehyde* (kcal/mol)

Dihedral angle τ	$\tau = 0°$		$\tau = 90°$
Kékulé structure	A	B	A = B
Nuclear repulsion energy	101959.09	101959.09	101675.40
E_0 (zeroth-order energy)	−45105.086	−45104.958	−45105.515
Delocalization energy	−312.503	−313.653	−309.032
Intra-bond correlation energy	−115.082	−115.131	−115.134
Inter-bond correlation energy	−150.998	−149.808	−149.092
E_2 (second-order energy correction)	−578.582	−578.592	−573.258
E_0+E_2	−45683.668	−45683.550	−45678.773
Delocal. 2 bonds correl. interaction[a])	−12.651	−11.821	−11.415
1 Bond correl. 2 bond correl. interaction	62.156	61.361	61.221
Delocal. delocal. interaction	−44.617	−44.374	−45.670
2 Bond correl. 2 bond correl. interaction	47.364	44.561	44.860
E_3 (third-order energy correction)	52.252	49.724	48.993
$E_0+E_2+E_3$	−45631.418	−45633.826	−45629.781

[a]) Delocal. stands for 'delocalization' and correl. for 'correlation'.

CNDO/2 method using standard geometry is well-known [32] [33] [63]. The height of barrier is also better described by the PCILO method than by the *ab initio* STO-3G calculation using standard geometry *(Table 2)*.

d) *Aniline.* For a study of the inversion of the amino group in aniline a pure pyramidal hybridization at the N-atom is assumed *(Fig. 5)*. The angle of pyramidalization α is interrelated to the bond angle ∢HNH (β) by [42]

$$\operatorname{tg}\alpha = \cos(\beta/2) \cdot \sqrt{\operatorname{tg}^2\beta - \operatorname{tg}^2(\beta/2)}$$

The dihedral angle ϕ is given by [42]

$$\operatorname{tg}\phi = \operatorname{ctg}(\beta/2) \cdot \sin\alpha$$

The lone-pair F *(Fig. 5)* is assumed to be orthogonal to the plane of the phenyl system and the angle ∢CNF is fixed at 90°. In this model the inversion is only a function of the angle of pyramidalization α. This angle is varied in 15° steps within the range of 0° and 75°.

The PCILO computation correctly predicts the pyramidal structure to be the most stable one with $\alpha = 55°$. A double-minimum potential function for the inversion of the amino group is found with a barrier of 7.3 kcal/mol. The two *Kékulé* structures A and B *(Fig. 6)* have the same zeroth-order energy and the CI-terms give the same third-order energy. The three different criteria are equivalent. The barrier of inversion is found as too high compared with experimental data *(Table 2)*, which is similar to the CNDO/2 results. *Ab initio* STO-3G calculations predicted also a too high barrier to inversion, only an extended basis set yield a quantitatively correct barrier and angle of pyramidalization [42]. On the other hand surprisingly good results were obtained by the INDO method [40]. In the present PCILO calculation the zeroth-order wave function overestimates the delocalization contributions in the CI-perturbative treatment. A similar shortcoming of both PCILO and CNDO/2 is also observed by *Weller & Lochmann* [64] in a series of aliphatic amines in predicting the inversion barriers.

By rotating the amino group the two *Kékulé* structures are no more equivalent *(Table 5)*. The conformational energy map shows *(Fig. 7)* that the choice of the *Kékulé* structure in the region for α larger than 50° is important. With $\alpha = 55°$ the

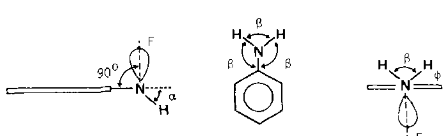
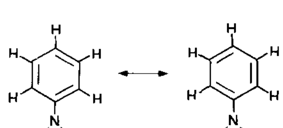


Fig. 5. *Definition of angles in aniline*



Kékulé A *Kékulé* B Fig. 6. *Designation of the* Kékulé *structures of aniline*

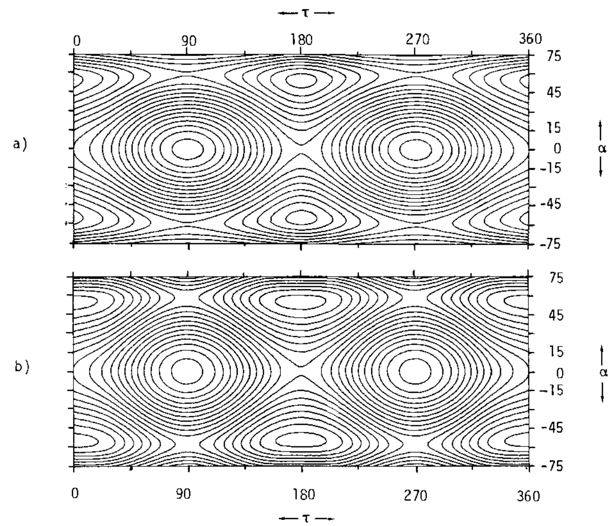


Fig. 7. *Conformational energy maps of aniline a)* Kékulé *structure A, b)* Kékulé *structure B* (the isoenergy curves run from 0 to 19 kcal/mol in 1 kcal/mol steps)

rotational barrier for the amino group is calculated for *Kékulé* structure A as 5.80 kcal/mol and for *Kékulé* structure B as 7.93 kcal/mol. Compared with experimental data *Kékulé* structure A seems to describe the barrier more reasonably *(Table 2)*. This *Kékulé* structure is predicted by the E_3-criterion, whereas on the base of the E_0-criterion the structure B may be chosen. The pronounced energy difference between the two *Kékulé* structures in the third-order energy (ΔE_3^{AB}=2.1 kcal/mol) during rotation shows similar behaviour as in benzaldehyde. The *Kékulé* structure A is predominantly stabilized by delocalization contributions in the second- and third-order terms corrected by interbond correlation energy *(Table 5)*. Therefore, the (A + B/2)-criterion

Table 5. *PCILO energy contributions of aniline* (kcal/mol)

Angle of pyramidalization α Dihedral angle τ *Kékulé* structure	$\alpha=0°$ $\tau=0°$ A=B	$\alpha=55°$ $\tau=0°$ A=B	$\alpha=55°$ $\tau=90°$ A	 B
Nuclear repulsion energy	87413.461	87661.348	87607.836	87607.836
E_0 (zeroth-order energy)	−36987.945	−36979.501	−36980.206	−36980.235
Delocalization energy	−288.659	−302.032	−294.359	−292.488
Intra-bond correlation energy	−101.136	−101.474	−101.475	−101.465
Inter-bond correlation energy	−118.106	−118.453	−117.356	−118.348
E_2 (second-order energy correction)	−507.902	−521.958	−513.188	−512.301
E_0+E_2	−37495.846	−37501.459	−37493.394	−37492.536
Delocal. 2 bonds correl. interaction[a])	−10.729	−10.679	−10.902	−11.015
1 Bond correl. 2 bond correl. interaction	46.220	56.327	45.895	46.351
Delocal. delocal. interaction	−43.463	−45.212	−46.031	−46.250
2 Bond correl. 2 bond correl. interaction	36.353	36.253	35.474	36.600
E_3 (third-order energy correction)	28.374	26.684	24.435	25.688
$E_0+E_2+E_3$	−37467.473	−37474.776	−37468.960	−37466.848

[a]) Delocal. stands for 'delocalization' and correl. for 'correlation'.

would lead to an overestimation of *Kékulé* structure B and to a too high rotational barrier of 6.87 kcal/mol compared with experimental data. The PCILO result of the rotation of the amino group is comparable to the INDO and *ab initio* results, whereas CNDO/2 predicted a too high barrier to rotation with $a = 0°$ *(Table 2)*.

e) *Phenol.* It is well-established that phenol is a planar molecule with a rotational barrier of 3.4 kcal/mol *(Table 2)*. Because the height of barrier may be associated with the moderably large degree of double-bond character of the C,O-bond, it is interesting to note the effect of the lone-pair description of the O-atom by the canonical hybrid function sp^3 or sp^2 (σ- or π-form). The employed geometries of the fictitious atoms F_i are defined in *Figure 9*. In general, we deduce the fictitious bond angle $\sphericalangle R_2OF$ (ϕ) as a function of the bond angle $\sphericalangle R_2OR$ (a) and the dihedral angle R_1R_2OF (γ) for the σ-form *(Fig. 9)*:

$$\cos\phi = -\cos(a/2)\cdot\cos(\gamma/2)$$

Assuming $\gamma = 109.5°$, it follows:

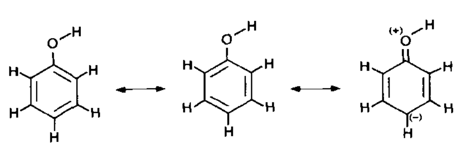
$$\cos\phi = -0.57715\cos(a/2)$$

For the fictitious bond angle $\sphericalangle R_2OF$ (ϕ) in the π-form *(Fig. 9)* we take $\phi = 180° - (a/2)$. The bond angle $\sphericalangle CCO$ is taken as 122.2° in the planar conformation and as 120.0° in the orthogonal one.

The energy difference of the σ,π-forms and the *Kékulé* structures during the rotation of the hydroxyl group are shown in *Table 6*. In all cases phenol is predicted to be planar by PCILO calculation.

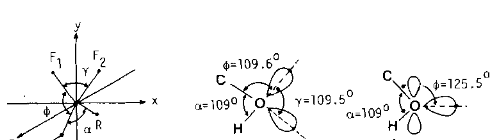
The σ- and π-descriptions are energetically not equivalent. Both *Kékulé* structures of the σ-form have a better zeroth-order energy ($\Delta E_0^{\sigma\pi} = 9.5$ kcal/mol) in the planar and orthogonal conformation. The third-order energy of the π-form is favored in the planar conformation due to a larger delocalization energy ($\Delta E_3^{\sigma\pi} = 1.1$ kcal/mol), whereas in the orthogonal state the π-form is smaller in energy ($\Delta E_3^{\sigma\pi} = 0.8$ kcal/mol). This is caused mainly from changes in the delocalization energy due to rotation, which is 2.8 kcal/mol in the σ-form and 8.2 kcal/mol for the π-form, respectively.

In the planar conformation the energy differences between the *Kékulé* structures of the same hybridization type are $\Delta E_{3\sigma}^{AB} = 0.5$ and $\Delta E_{3\pi}^{AB} = 0.66$ kcal/mol,



Kékulé A *Kékulé* B *Kékulé* C

Fig. 8. *Designation of the* Kékulé *structures of phenol*



σ-Form π-Form

Fig. 9. *Geometry of O-atom in phenol*

Table 6. *PCILO energy contributions of phenol* (kcal/mol)

Dihedral angle τ	$\tau=0°$				$\tau=90°$	
Hybridization type of oxygen atom	σ		π		σ	π
Kékulé structure	A	B	A	B	A=B	A=B
Nuclear repulsion energy	87179.100	87179.100	87179.100	87179.100	87137.842	87137.842
E_0 (zeroth-order energy)	−40761.781	−40761.759	−40751.052	−40751.034	−40762.600	−40752.125
Delocalization energy	−276.062	−275.263	−291.402	−290.221	−272.839	−282.645
Intra-bond correlation energy	−98.191	−98.199	−97.578	−97.584	−98.195	−97.580
Inter-bond correlation energy	−117.146	−116.218	−116.839	−115.933	−116.146	−115.861
E_2 (second-order energy correction)	−491.399	−489.680	−505.820	−503.738	−487.181	−496.086
E_0+E_2	−41253.180	−41251.439	−41256.872	−41254.772	−41249.780	−41248.211
Delocal. 2 bonds correl. interaction[a])	−10.555	−10.556	−10.515	−10.516	−10.718	−10.648
1 Bond correl. 2 bond correl. interaction	46.090	45.657	45.914	45.495	45.690	45.529
Delocal. delocal. interaction	−47.740	−47.662	−44.992	−45.142	−46.601	−47.213
2 Bond correl. 2 bond correl. interaction	35.502	34.607	35.384	34.506	34.828	34.724
E_3 (third-order energy correction)	23.294	22.044	25.786	24.340	23.200	22.392
$E_0+E_2+E_3$	−41229.886	−41229.395	−41231.086	−41230.431	−41226.581	−41225.819

[a]) Delocal. stands for 'delocalization' and correl. for 'correlation'.

favoring in both hybrid forms the *Kékulé* structure A. In the orthogonal conformation the energies of the *Kékulé* structures of the same hybridization type are degenerate.

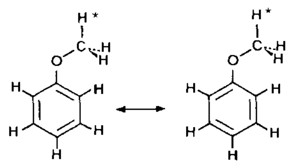
The criteria for choosing an appropriate form (σ and π) and *Kékulé* structure (A and B) are suggested as follows,

E_0-criterion → σ-form, *Kékulé* structure A
E_3-criterion → planar: π-form, *Kékulé* structure A
orthogonal: σ-form, *Kékulé* structure A = B

A comparison between experimental data and the results of PCILO calculations shows *(Table 2)* that the barrier to internal rotation is predicted to be too high by the π-form, whereas the σ-form gives better agreement with experimental data. It seems that the hybridization type of the O-atom determines predominantly the height of rotational barrier, while the choice of the *Kékulé* structures are not so important.

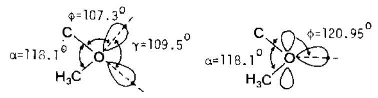
The PCILO value of 3.0 kcal/mol with the σ-(A + B/2)-form is similar to those calculated by CNDO/2 method using standard geometry *(Table 2)*. The PCILO value of 4.94 kcal/mol with the π-(A + B/2)-form is comparable with the *ab initio* STO-3G results using standard geometry, but are still not in good agreement with the experimental values.

f) *Anisole.* The internal rotation of the methoxy group around the two axes τ_1 (CCOC) and τ_2 (COCH*) seems to be due to a balance between the steric interaction of the methyl group and the *ortho*-H-atoms of the phenyl system which



Kékulé A   *Kékulé* B

Fig. 10. *Designation of the* Kékulé *structures of anisole*



σ-Form   π-Form

Fig. 11. *Geometry of O-atom in anisole*

favors a non-planar conformation, and the π-overlap which favors a planar heavy atom skeleton *(Fig. 10)*. By experimental methods the conformation and rotational barrier of the methoxy group are not definitely determined. It is only indicated that the most stable conformation is planar as reviewed in [50]. The employed geometries of the fictitious atoms are given in *Figure 11*. In view of geometry relaxation, the bond angle ∢CCO is taken as 124.4° in the planar conformation, and as 120.0° in the orthogonal one. For the dihedral angle 30° and 60° this bond angle is linear-interpolated.

The computational results of the rotation around τ_1, fixed with τ_2 at 180°, are given in *Table 7*. The planar conformation is found to be the most stable one in all cases. The σ-form has a lower zeroth-order energy in the planar ($\Delta E_0^{\sigma\pi} = 7.57$ kcal/mol) and the orthogonal conformation ($\Delta E_0^{\sigma\pi} = 7.05$ kcal/mol). The third-order

Table 7. *PCILO energy contributions of anisole with* τ_2 *(COCH*) = 180°* (kcal/mol)

Dihedral angle τ_1	$\tau_1 = 0°$				$\tau_1 = 90°$	
Hybridization of oxygen atom	σ		π		σ	π
Kékulé structure	A	B	A	B	A = B	A = B
Nuclear repulsion energy	112533.58	112533.58	112533.58	112533.58	112329.59	112329.59
E_0 (zeroth-order energy)	−46185.865	−46185.821	−46178.294	−46178.249	−46187.712	−46180.662
Delocalization energy	−296.302	−295.695	−310.967	−309.834	−292.747	−301.363
Intra-bond correlation energy	−117.228	−117.243	−116.549	−116.565	−117.235	−116.552
Inter-bond correlation energy	−124.127	−123.126	−123.621	−122.647	−123.133	−122.647
E_2 (second-order energy correction)	−537.657	−536.064	−551.138	−549.046	−533.115	−540.562
$E_0 + E_2$	−46723.522	−46721.885	−46729.432	−46727.295	−46720.826	−46721.225
Delocal. 2 bonds correl. interaction[a])	−10.634	−10.638	−10.558	−10.561	−10.824	−10.714
1 Bond correl. 2 bond correl. interaction	48.365	47.891	48.072	47.617	47.960	47.681
Delocal. delocal. interaction	−48.669	−47.899	−44.266	−43.583	−47.439	−46.332
2 Bond correl. 2 bond correl. interaction	36.103	35.199	35.199	35.088	35.521	35.402
E_3 (third-order energy correction)	25.162	24.552	29.213	28.556	25.217	26.035
$E_0 + E_2 + E_3$	−46698.360	−46697.333	−46700.219	−46698.739	−46695.609	−46695.189

[a]) Delocal. stands for 'delocalization' and correl. for 'correlation'.

energy in the planar conformation is lower for the π-form ($\Delta E_3^{\sigma\pi} = 1.63$ kcal/mol), but in the orthogonal conformation the σ-form ($\Delta E_3^{\sigma\pi} = 0.42$ kcal/mol) has a lower energy. Similar to phenol this change in the third-order energy is mainly due to changes in the delocalization energy, which is 3.25 kcal/mol for the σ-form and 9.04 kcal/mol for the π-form. The energy differences between two *Kèkulé* structures of the same hybridization type are $\Delta E_{3\sigma}^{AB} = 1.0$ kcal/mol and $\Delta E_{2\pi}^{AB} = 1.5$ kcal/mol in the planar conformation. In the orthogonal conformation the two *Kèkulé* structures are degenerate.

The application of the criteria for the choice of the appropriate description may be indicated as follows,

E_0-criterion → σ-form, *Kèkulé* structure A
E_3-criterion → planar: π-form, *Kèkulé* structure A
orthogonal: σ-form, *Kèkulé* structure A = B

Compared with experimental data the choice of the π-form gives a too high barrier while by the σ-form a more reasonable value is achieved. As in phenol, the height of the rotational barrier is determined mainly by the hybridization type of the O-atom, seldom by the *Kèkulé* structures. It may be suggested that the delocalization in the π-form is overestimated in the planar conformation.

These results for the σ-form with respect to the barrier to internal rotation τ_1 (2.1 kcal/mol) agree well with those obtained from CNDO/2 calculations using standard geometry (1.0 and 1.76 kcal/mol) and MINDO/3 (1.28 kcal/mol), whereas in the *ab initio* STO-3G studies using standard geometry the orthogonal conformation is almost degenerate in energy with the planar conformation and INDO even fails in predicting the most stable conformation *(Table 2)*.

The conformational energy maps of anisole with respect to the torsional angles τ_1 and τ_2 are shown in *Figure 12*. As noted from the maps the rotational barrier height is smaller in magnitude due to a rotation of the methyl group, resulting from decreased steric interaction between the methyl group and the *ortho*-H-atoms of the phenyl system. Furthermore it is worthwhile to note that the σ- and π-forms do not influence the rotation about τ_2 significantly *(cf. Table 8)*. The rotation of the methyl group with $\tau_1 = 90°$ is expected to be symmetrical. As shown in *Figure 13*, the separate *Kèkulé* structures A and B gives an unsymmetrical potential function, whereas the superposition (A + B/2) symmetrize the results. Therefore, the (A + B/2)-criterion seems to give the most appropriate description of the rotational behaviour of anisole.

Table 8. *Rotational barriers of the methyl group in anisole in kcal/mol* (τ_2: 180° → 210°)[a])

τ_1	σ		π	
	A	B	A	B
0°	3.403	3.301	3.600	3.201
30°	1.309	1.331	1.622	1.264
60°	0.977	0.678	0.888	0.692
90°	0.715	0.715	0.729	0.730

a) σ and π stand for the hybridization type and A and B for the *Kèkulé* structure.

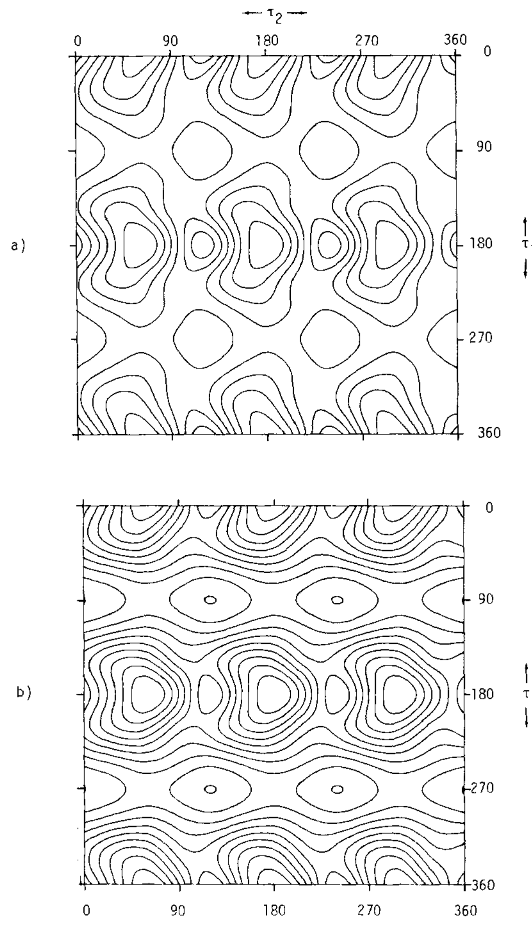


Fig. 12. *Conformational energy maps of anisole a) σ(A + B/2)-form, b) π(A + B/2)-form* (the isoenergy curves run from 0 to 3.5 kcal/mol in 0.5 kcal/mol steps)

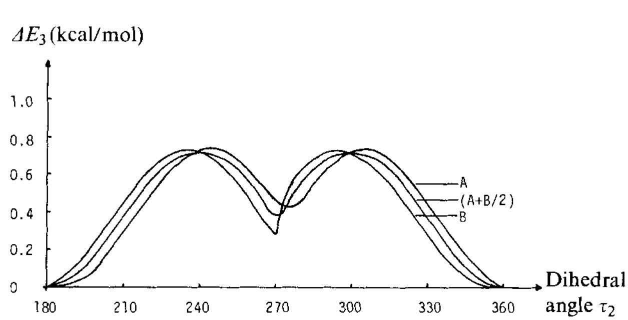


Fig. 13. *Rotation of the methyl group in anisole with $\tau_1 = 90°$*

3. Conclusions. – The *Kékulé* structures and hybridization types of O-atom suggested by the application of the E_0- and E_3-criteria are collected in *Table 9.* In phenol and anisole the hybridization type of the O-atom determines predominantly the height of barrier to internal rotation. It seems advisable to employ an sp^3-hybridized O-atom in the PCILO computations, since in phenol and anisole this hybridization type offers results comparable with experimental values. This hybridization type is also predicted from the E_0-criterion, whereas the E_3-criterion does not give a consistent picture. The higher barrier to internal rotation with the sp^2-hybridized form of phenol and anisole may arrise from the overestimation of the delocalization energy in the planar conformation. As in the case of the rotation of the methyl group in anisole, the influence of the hybridization type of O-atom during this rotation seems to be negligible, if the rotational axis is not adjacent to the aromatic system.

As summarized in *Table 9,* the (A + B/2)-criterion generally offers a good quantitative description of internal rotations of molecules considered in the study. The E_0-criterion does not seem to be appropriate since the barriers to internal rotation in aromatic systems predominantly arrise from delocalization effects. In computations with the PCILO method the CI-part must also be considered in aromatic systems. For molecules, whose both *Kékulé* structures are not comparable in their third-order energy ($\Delta E_3^{AB} > 2$ kcal/mol), it does not seem appropriate to employ the (A + B/2)-scheme for the description of the whole system. The internal rotations of benzaldehyde and aniline are better described with the *Kékulé* structures proposed by the E_3-criterion. It is also suggested that in the strongly localized picture of PCILO the weights of two *Kékulé* structures in certain molecules may be different.

The general conclusion from this study is that, for the calculation of the internal rotation of a bond adjointed to an aromatic system, a criterion of differences between the two *Kékulé* structures ($\Delta E_3^{AB} \gtrless 2$ kcal/mol) must be chosen at first, and then depending on the first criterion the application of the E_3- or (A + B/2)-criterion should be determined. These findings are summarized in *Figure 14* for further applications of PCILO calculations in other aromatic systems.

For the barrier to internal rotation of the groups not directly connected to an aromatic system (*e.g.* the methyl group in anisole), the influence of energy differences of the two *Kékulé* structures is not important. But attention should be

Table 9. *Predictions from variational criteria for the appropriate energy value in calculations of monosubstituted benzenes Ph-X*

X	E_0-criterion	E_3-criterion	Appropriate form compared with experimental data
CH_3	A = B	opposite	(A + B/2)
NO_2	A	A	(A + B/2)
CHO	A	B	B
NH_2	A ~ B	A	A
OH	σA	dependent upon conformation	σA and σ(A + B/2)
OCH_3	σA	dependent upon conformation	σ(A + B/2)

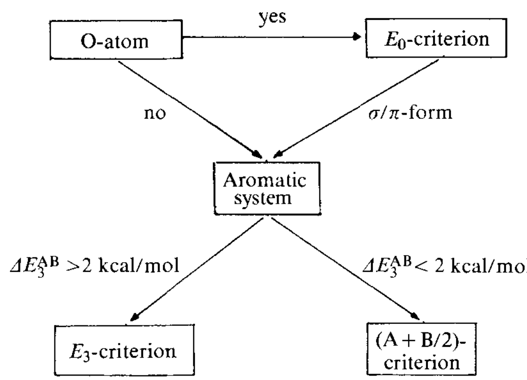


Fig. 14. *Choice of energy criteria in treating substituted aromatic systems by the PCILO method*

paid to the possibility of differences in the intramolecular interaction of atoms far from the aromatic system with those adjointed to it.

With the above mentioned remedies the PCILO method provides quite a good result in determining the barrier to internal rotations. Except for aniline, the PCILO barriers are in general smaller in magnitude compared to experimental data. Independent on the choice of *Kékulé* structure and hybridization type of O-atom, the most stable conformation of molecules considered in this study is predicted well by the PCILO method, whereas other semiempirical methods are shown to be not reliable in general in predicting the most stable conformation of substituted benzenes (*cf. Table 2*).

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