A Theoretical Study of Substituted Cyclopentanones and their Enols

Meisa S. Al-Noeemat, Reem A. Al-Ma'ani, and Salim M. Khalil

Chemistry Department, College of Science, University of Mutah, Karak, Jordan

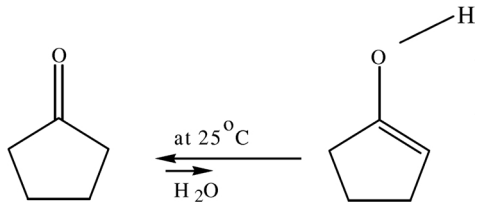
Reprint requests to Prof. S. M. K.; e-mail: qukhalil@mutah.edu.jo

Z. Naturforsch. **58a,** 738 – 748 (2003); received June 20, 2003

MINDO-Forces calculations with complete geometry optimization have been performed on cyclopentanone and its enol counter part, perfluorination of cyclop entanone and its enol counterpart and X-cyclopentanones and their X-enols, where X is NO_2, CF_3, CN, OH, NH_2 and O^-. It was found that ketone is more stable than its enol counterpart. Perfluorination destabilizes ketone on the expense of enol. These results agree with the experimental results and density functional theory calculations. All substituents are destabilizing except O^- in the case of cyclopentanone. It was found that NO_2 and CF_3 behave as strong electron withdrawing groups, CN and NC show amphielectronic behavior, and the substituents OH,NH_2 and O^- behave as electron releasing groups with O^- being strongest. Geometrical parameters, heats of formation, entropies, and Gibbs free energies are reported.

Key words: Perfluorocyclopentanones; Substituted Cyclopentanones; Keto-enol Equilibria.

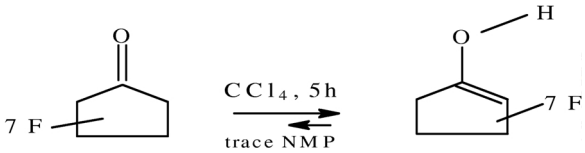
Keto-enol tautomerism of cyclopentanones has often been studied experimentally. Daubois and coworkers [1] have studied the keto-enol tautomerism of simple carbonyl compounds including cyclopentanone; both kinetic and thermodynamic data were reported. For cyclopentanone, the ketone was found to be more stable ($K_{enol-keto} = 1.01 \cdot 10^{-8}$ at 25 °C in aqueous solution).



Also in [2] it was found, that cyclopentanone is more stable than its enol (K_{eq} = [enol]/[ketone] = $4.8 \cdot 10^{-3}$).

Highly fluorinated cyclopentanones and their enols were studied by Lindler and Lemal [3] at 25 °C in carbon tetrachloride containing a trace of N-methyl pyrrolidine (NMP) as catalyst. The results obtained showed that the equilibrium between 2H-perfluorocyclopentanone and its enol lies on the enol side. This was confirmed by ^{19}F NMR spectroscopy.

An ab initio study of the keto-enol tautomerism [3] showed that the ketone is the more stable form. The



same study showed that for 2H-perfluorocyclopentanone and its enol, even at high levels of ab initio theory, the ketone is the stabler form. Kwon [4], however, using density functional theory calculations, has recently reported that the enol perfluorocyclopentene-1-ol is much stabler than its ketone. Perfluorinated cyclopentanone with two geminal α-hydrogens (2,2H-perfluorocyclopentanone) was predicted to be more stable than its enol [3, 4].

In the present paper the keto-enol tautomerism for the parent cyclopentanone, highly fluorinated cyclopentanone and the effect of substituents (NO_2, CF_3, CN, NC, OH^-, NH_2, O^-) on the keto-enol tautomerism is reinvestigated by the MINDO-Forces MO method [5], whereby the molecular energy of the compounds obtained from semiempirical MINDO/3 MO [6] was completely minimized by the Mutargh-Sargent technique [7]. The derivative of the energy was calculated according to Pulay's method [8]. The program allows the variation of the β-parameter with geometrical change in a consistent way. A full description of the program and its application is giving in [5a].

0932–0784 / 03 / 1200–0738 $ 06.00 © 2003 Verlag der Zeitschrift für Naturforschung, Tübingen · http://znaturforsch.com

Table 1. Heats of formation (ΔH_f in kcal mol^{-1}) and entropies (cal mol^{-1}K^{-1}) for parent and perfluorinated cyclopentanones and their enol counterparts, as calculated by the MINDO-Forces method (see Table 2 for numbering).

Molecule No.	Heat of formation	Entropy
1	−58.046	47.768
2	−52.956	47.028
3	−420.9	58.193
4	−422.645	62.576

1. Results and Discussion

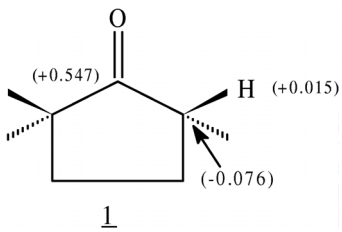
1.1. Parent Cyclopentanone and its Enol Counterpart with Perfluorination

MINDO-Forces calculations have been performed first on the parent cyclopentanone and its enol (without perfluorination), and then on perfluorination of cyclopentanone and its enol counterpart.

The calculated heats of formation and entropies for the parent and perfluorinated cyclopentanones and their enol counterparts are shown in Table 1.

The geometrical parameters (bond lengths and bond angles) for the parent and perfluorinated cyclopentanones and their enol counterparts after complete optimization of the geometry are given in Table 2, where it can be seen that the cyclopentanone 1 is symmetric in bond angles and bond lengths. The internal angles C1C2C3 and C4C5C1, (107.8 degrees), and also the other two internal angles C2C3C4 and C3C4C5 (108.1 degrees) are equal. The symmetry is also noticed in the bond lengths; the lengths C1-C2 and C1-C5, and also the lengths C2-C3 and C4-C5 are equal.

For the enol counterpart 2, the symmetry in bond lengths and bond angles was not observed. The electron densities and charge distributions for the parent and perfluorinated cyclopentanones and their enol counterparts are shown in Table 3.



Cyclopentanone

In cyclopentanone 1, the slight acidity of α-hydrogens, due to the presence of the carbonyl group, is shown through the slightly positive charge carried by these hydrogens (Table 3).

The electron density distribution also predicts that the carbonyl group is stabilized by the electrostatic attraction between the positive carbonyl carbon and the two negative α-carbons [9, 10].

Thermodynamic properties of the keto-enol system for parent and perfluorinated cyclopentanones and their most stable enol counterparts are given in Ta-

Table 2. Optimized geometrical parameters (bond lengths in Å, bond angles in degrees) calculated by MINDO-Forces for the parent and perfluorinated cyclopentanones with their enol counterparts.

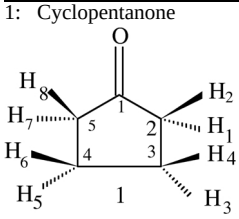
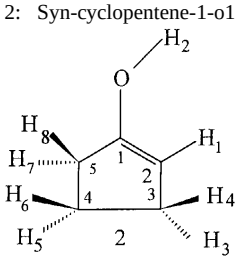
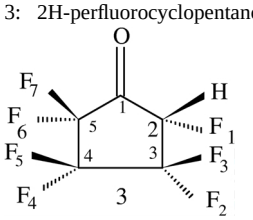
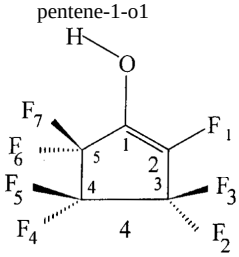
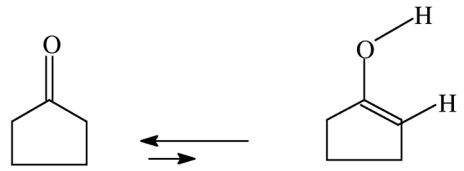
Molecule No. and name	Bond length	Calcd. Bond length	Bond angle	Calcd. Bond angle
1: Cyclopentanone	C1=O	1.203	<OC1C2	125.9
	C1-C2	1.527	<H1C2H2	103.8
	C2-C3	1.523	<C1C2C3	107.8
	C3-C4	1.525	<C2C3C4	108.1
	C4-C5	1.523	<C3C4C5	108.1
	C5-C1	1.527	<C4C5C1	107.8
	C1-H1	1.115	<C5C1C2	108.2
2: Syn-cyclopentene-1-o1	C1-O	1.321	<OC1C2	130.0
	C1-C2	1.364	<H2OC1	111.4
	C2-C3	1.499	<C1C2H1	127.8
	C3-C4	1.529	<C1C2C3	111.4
	C4-C5	1.533	<H3C3H4	102.3
	C5-C1	1.519	<C2C3C4	105.3
	O-H2	0.953	<C3C4C5	107.5
	C2-H1	1.099	<C4C5C1	104.2
	C3-H3	1.119	<C5C1C2	111.6
3: 2H-perfluorocyclopentanon	C1=O	1.192	<OC1C2	126.9
	C1-C2	1.534	<H1C2F1	105.4
	C2-C3	1.508	<C1C2C3	108.2
	C3-C4	1.513	<F2C3F3	107.9
	C4-C5	1.513	<C2C3C4	109.1
	C5-C1	1.529	<C3C4C5	106.8
	C2-F1	1.400	<C4C5C1	109.7
	C2-H	1.097	<C5C1C2	105.9
	C3-F2	1.366		
	C3-F3	1.365		
4: Anti-perfluorocyclo-pentene-1-o1	C1-O	1.309	<OC1C2	126.0
	C1-C2	1.369	<HOC1	110.4
	C2-C3	1.488	<C1C2F1	124.9
	C3-C4	1.520	<C1C2C3	114.6
	C4-C5	1.520	<F2C3F3	106.4
	C5-C1	1.518	<C2C3C4	105.0
	O-H	0.951	<C3C4C5	105.5
	C2-F1	1.370	<C4C5C1	108.4
	C3-F2	1.363	<C5C1C2	106.4

Table 3. Electron densities and charge distributions as calculated by MINDO-Forces for parent and perfluorinated cyclopentanones and their enol counterparts (see Table 2 for numbering).

Mol. No.	Atom	Electron Densities	Charge	Mol. No.	Atom	Electron Densities	Charge
1	C1	3.453	0.547	3	C1	3.600	0.400
	O	6.484	−0.484		O	6.319	−0.319
	C2	4.076	−0.076		C2	3.830	0.170
	H1	0.985	0.015		H	0.939	0.061
	H2	0.985	0.015		F1	7.257	−0.257
	C3	3.939	0.061		C3	3.339	0.661
	H3	1.024	−0.024		F2	7.299	−0.299
	H4	1.024	−0.024		F3	7.356	−0.356
	C4	3.939	0.061		C4	3.414	0.586
	H5	1.024	−0.024		F4	7.302	−0.302
	H6	1.024	−0.024		F5	7.304	−0.304
	C5	4.076	−0.076		C5	3.404	0.596
	H7	0.985	0.015		F6	7.314	−0.314
	H8	0.985	0.015		F7	7.324	−0.324
2	C1	3.645	0.355	4	C1	3.827	0.173
	O	6.431	−0.431		O	6.330	−0.330
	H2	0.748	0.252		H	0.717	0.283
	C2	4.250	−0.250		C2	3.879	0.121
	H1	0.966	0.034		F1	7.206	−0.206
	C3	3.869	0.131		C3	3.311	0.689
	H3	1.045	−0.045		F2	7.332	−0.332
	H4	1.045	−0.045		F3	7.332	−0.332
	C4	3.949	0.051		C4	3.413	0.587
	H5	1.028	−0.028		F4	7.305	−0.305
	H6	1.028	−0.028		F5	7.305	−0.305
	H7	1.013	−0.013		F6	7.344	−0.349
	H8	1.013	−0.013		F7	7.349	−0.349

ble 4. ΔG_r is positive ($\Delta G_r = 5.311$ kcal/mol) for the parent keto-enol system, which indicates that the reaction is not spontaneous (the equilibrium lies to the ketone side).

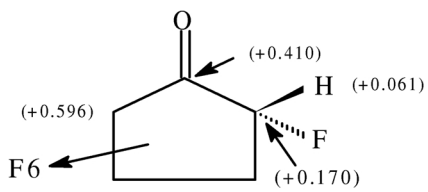


Cyclopentanone Syn-cyclopentene-1-o1

This shift in equilibrium may be explained by the fact that the α-hydrogens are only slightly acidic (Table 3). This agrees with the experimental studies [1–3, 11, 12].

On perfluorination of cyclopentanone, the symmetry in bond lengths and bond angles of the perfluorinated cyclopentanone 3 disappears (Table 2). From the calculated heats of formation (Table 1), the perfluorocyclopentene-1-ol 4 is more stable than 2H-perfluorocyclopentanone 3 by about 2 kcal/mol. This is consistent with the experimental results [3]. Density functional theory calculations [4] show that ketone is slightly more stable than enol at B3LYP/6-31G** and B3LYP/6-31+G*, but at higher levels the theory predicts enol to be more stable than ketone. The energy gap between ketone and enol is about 2 kcal/mol at the B3LYP/6-311++G**//B3LYP/6-31G* level [4] which agrees with the present calculations. However ab initio methods [3] at the HF/6-311G*//HF/6-31G** and MP2/6-311G**//HF/6-31G** levels gave no improvement to the calculated energy gap and failed to support the experimental equilibrium constant.

The electron density decreases on the carbon atom to which the fluorine substituent is attached (compound 3) and also on α-hydrogen (making it more acidic). The electron density distribution predicts a destabilized carbonyl group due to electrostatic repulsion between the carbonyl carbon (which carries a positive charge) and the two α-carbons (which both carry positive charges) [10].



3

2H-perfluorocyclopentanone

This also agrees with the ab initio calculations (HF/6-31 G**) [3], which suggest that there is electrostatic repulsion between the positive carbonyl carbon (+0.33) and the two positive α-carbons (+0.47 and +0.27). Density functional calculations [4] also show that there is an electrostatic repulsion between an α-carbon and a carbonyl carbon in ketone, which suggests a destabilization of ketone. Thus the enol form is favored over the ketone form.

Thermodynamic calculations (Table 4) for the perfluorinated keto-enol system show that the reaction is spontaneous ($\Delta G_r = -3.415$ kcal/mol, the shift in equilibrium to the enol side), which is different from the parent system(not spontaneous). This shift to the enol side may be a result of an increase in the acidity of the α-hydrogen in the perfluorinated ketone (+0.061), compared to the parent one (+0.015), which could be a good motive for the reaction to be spontaneous. The stabilization effect of perfluorination on cyclopen-

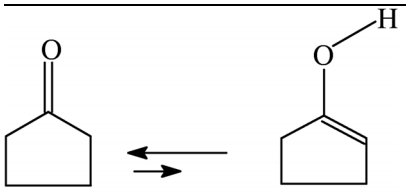
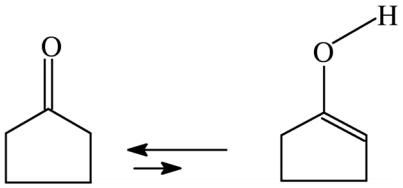
Keto-Enol System	ΔH_r (kcal mol^{-1})	ΔS_r (kcal mol/k)	ΔG_r (kcal mol^{-1})
	5.09	−0.74	5.311
	−2.004	4.734	−3.415

Table 4. Thermodynamic properties of keto-enol system for parent and perfluorinated cyclopentanones and enol counterparts.

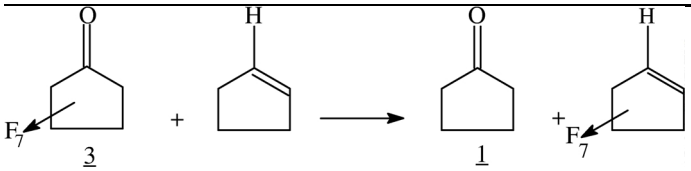
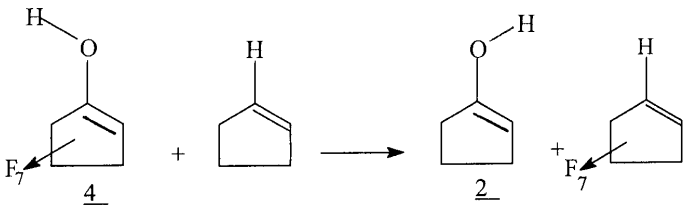
	ΔH_r (kcal mol^{-1})
	−11.844
	−5.009

Table 5. Stabilization effect of perfluorination on cyclopentanone and its enol counterpart.

tanone and its enol are evaluated using isodesmic reactions (Table 5). A negative value means destabilization by a substituent, and a positive value means stabilization by a substituent [5b, 5c].

The isodesmic reactions give more negative value for the ketone (−11.844 kcal/mol) than for the enol (−5.009 kcal/mol), which suggests that enol is relatively more stable than ketone. This agrees with ab initio calculation (HF/6-311G**//3-21G), where the isodesmic reactions give a more negative value for ketone (−18.7 kcal/mol) than for enol (−4.8 kcal/mol) [3]. This means that the shift in the equilibrium towards the enol side is attributed to ketone destabilization and not to enol stabilization, which again agrees with the present thermodynamic calculations and the experimental results [3].

1.2. Effect of Substituents

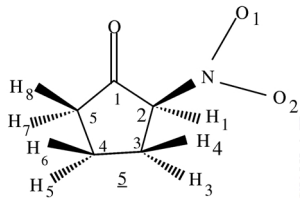
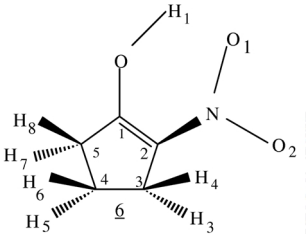
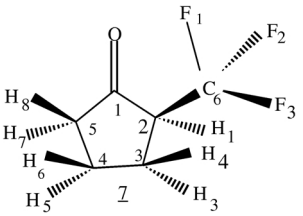
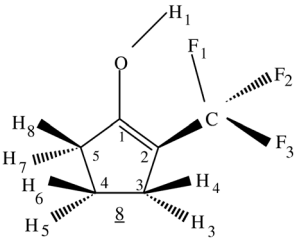
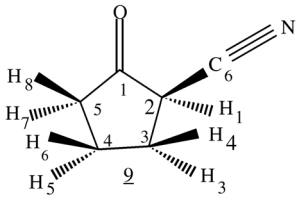
Although there is no available thermodynamic information, we have calculated the effect of substituents on this keto-enol system. It was found that the introduction of all substituents (NO_2, CF_3, CN, NC, OH^-, NH_2, O^-) at α-position stabilizes cyclopentanone more than that at β-position. For this reason we concentrate on the most stable substituted cyclopentanone and its enol counterpart.

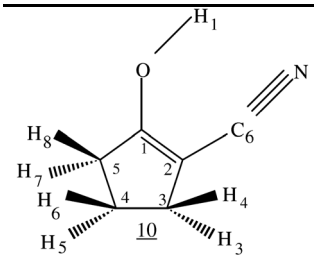
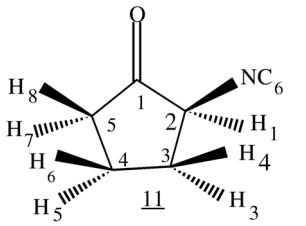
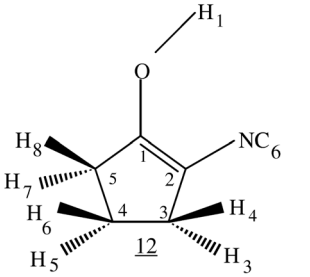
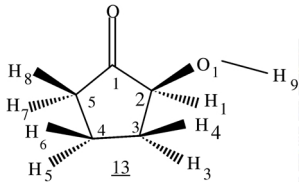
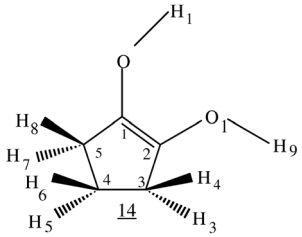
All substituents cause mainly changes in the geometrical parameters at which the substituent is attached (Table 6), and this is most pronounced in the case of O^- as substituent.

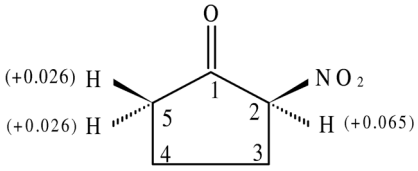
Effect of NO_2

The substituent NO_2 increases the electron density on C2 and decreases it on C1, C3, and H1 (compound 5), which suggests that NO_2 acts as electron withdrawing group. Also it shows that α-hydrogen carries more positive charge (more acidic) than that of the parent (compound 1). This increase in acidity may give a good motive for the enol formation.

Table 6. Calculated geometrical parameters of monosubstituted cyclopentanones and their enol counterparts.

Compounds	Bond lengths Å and bond angles in degrees
	C1=O,1.198; C1-C2,1.556; C2-C3,1.551; C3-C4,1.552; C4-C5,1.518; C5-C1,1.525; C2-H1,1.132; C2-N,1.474; N-O,1.223; C3-H3,1.114 OC1C2,126.7; C5C1C2,108.5; C1C2C3,105.7; C2C3C4,108.8; C3C4C5,108.3; C4C5C1,111.5; O1NO2,130.0
	C1-O,1.295; O-H,0.958; C1-C2,1.408; C2-C3,1.528; C3-C4,1.523; C4-C5,1.529; C5-C1,1.519;N-O,1.231;C3-H3,1.118 C1OH1,113.0; OC1C2,129.6; C1C2C3,109.5; C2C3C4,106.2; C3C4C5,107.7; C4C5C1,105.6; O1NO2,128.6
	C1=O,1.197; C1-C2,1.558; C2-C3,1.548; C3-C4,1.522; C5-C1,1.524; C2-C6,1.471; C6-F,1.328; C2-H1,1.124; C3-H4,1.115 OC1C2,123.6; C5C1C2,108.5; C1C2C3,105.9; C2C3C4,108.6; C3C4C5,108.6; C4C5C1,108.0; C2C6F1,102.3; FC6F,108.7
	C1-O,1.299; O-H,0.960;C1-C2,1.394; C2-C3,1.519; C3-C4,1.521; C4-C5,1.533; C5-C1,1.521; C2-C6,1.439; C6-F,1.329; C3-H4,1.116 H1OC1,110.3; OC1C2,126.5; C5C1C2,109.5; C1C2C3,111.6; C2C3C4,105.3; C3C4C5,107.4; C4C5C1,106.1; C1C2C6,127.4; FC6F,109.2
	C1=O,1.201; C1-C2,1.547; C2-C3,1.543; C4-C5,1.522; C5-C1,1.527; C2-C6,1.471; C2-H1,1.163; C6-N,1.163; C3-H4,1.117 OC1C2,125.1; C5C1C2,108.7; C1C2C3,106.1; C2C3C4,108.9; C3C4C5,108.2; C4C5C1,108.2

Compounds	Bond lengths Å and bond angles in degrees
	C1-O,1.315; O-H1,0.955; C1-C2,1.387; C2-C3,1.521; C3-C4,1.524; C4-C5,1.532; C5-C1,1.520; C2-C6,1.444; C6-N,1.327; C3-H3,1.119 OC1C2,127.5; H1OC1,110.6; C5C1C2,115.5; C1C2C3,109.8; C2C3C4,106.4; C3C4C5,107.2; C4C5C1,105.1; C1C2C6,128.4
	C1=O,1.202; C1-C2,1.546; C2-C3,1.543; C3-C4,1.524; C4-C5,1.522; C5-C1,1.525; C2-N,1.418; N-C6,1.151; C2-H1,1.131; C3-H3,1.117 OC1C2,125.0; C5C1C2,108.8; C1C2C3,106.2; C2C3C4,108.7; C3C4C5,108.4; C4C5C1,107.9
	C1-O,1.318; O-H1,0.956; C1-C2,1.386; C2-C3,1.518; C3-C4,1.523; C4-C5,1.533; C5-C1,1.518; C2-N,1.383; N-C6,1.155; C3-H3,1.119 OC1C2,127.5; H1OC1,110.3; C5C1C2,110.5; C1C2C3,111.1; C2C3C4,105.5; C3C4C5,107.4; C4C5C1,105.5; C1C2N,127.8
	C1=O,1.202; C1-C2,1.552; C2-C3,1.540; C3-C4,1.523; C4-C5,1.521; C5-C1,1.525; C2-O1,1.359; O1-H9,0.954; C3-H3,1.117 OC1C2,126.6; C5C1C2,108.1; C1C2C3,106.7; C2C3C4,108.5; C2O1H9,109.4
	C1-O,1.329; O-H1,0.956; C1-C2,1.379; C2-C3,1.511; C3-C4,1.522; C4-C5,1.534; C5-C1,1.516; C2-O1,1.338,O1-H9,0.952 OC1C2,129.3; H1OC1,108.5; C1C2C3,113.2; C2C3C4,104.3; C3C4C5,107.5; C2O1H9,109.7; H3C3H4,102.9

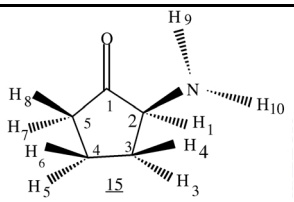
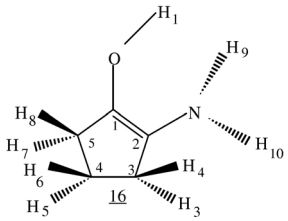
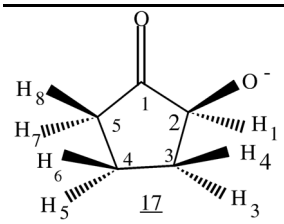
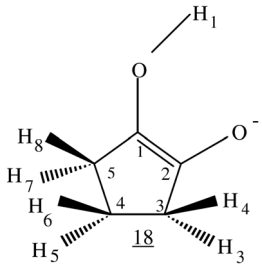


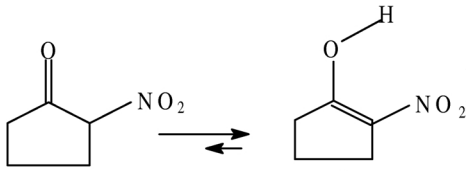
5

The enol formation is supported by the calculation of the Gibbs free energy (ΔG_r) (Table 7) of the nitro substituted keto-enol system. It was found that ΔG_r is very negative ($\Delta G_r = -17.16$ kcal mol^{-1}), which indicates a high tendency for the reaction to be spontaneous.

This tendency of the reaction to be spontaneous might be the result of a destabilization of the ketone

Table 6 (continued).

Compounds	Bond lengths Å and bond angles in degrees
 15	C1=O,1.202; C1-C2,1.546; C2-C3,1.543; C3-C4,1.524; C4-C5,1.521; C5-C1,1.526; C2-N,1.421; N-H,1.111; C2-H1,1.139; C3-H3,1.117 OC1C2,125.8; C5C1C2,108.9; C1C2C3,106.2; C2C3C4,108.7; C3C4C5,108.4; C4C5C1,107.9
 16	C1-O,1.327; O-H1,0.952; C1-C2,1.378; C2-C3,1.515; C3-C4,1.525; C4-C5,1.531; C5-C1,1.515; C2-N,1.398; N-H,1.024; C3-H3,1.120 OC1C2,129.2; H1OC1,110.3; C5C1C2,110.7; C1C2C3,111.2; C2C3C4,105.2; C3C4C5,107.5; C4C5C1,105.3; C1C2N,128.3; HNH,105.3
 17	C1-O,1.181; C1-C2,1.687; C2-C3,1.542; C3-C4,1.520; C4-C5,1.515; C5-C1,1.522; C2-O⁻,1.240; C2-H1,1.153; C3-H3,1.115 OC1C2,124.2; C5C1C2,107.6; C1C2C3,101.9; C2C3C4,112.2; C3C4C5,108.9; C4C5C1,109.3; H1C2O,118.7
 18	C1-O,1.305; O-H1,0.958; C1-C2,1.478; C2-C3,1.524; C3-C4,1.522; C4-C5,1.532; C5-C1,1.500; C2-O,1.219; C3-H3,1.116 OC1C2,126.0; H1OC1,109.7; C5C1C2,110.4; C1C2C3,107.7; C2C3H4,107.6; C3C4C5,107.6; C4C5C1,106.7; C1C2O,126.7



5 6

due to the high acidity of α-hydrogen as compared with the parent (Table 3).

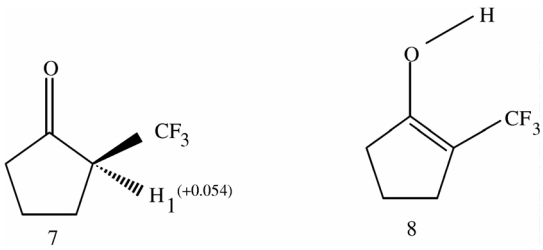
Also the stabilization effects of NO_2 on both ketone 5 and its enol counterpart 6 (Table 8) are often confirmed by using isodesmic reactions [13–15]. A negative value indicates less stability and a positive value more stability. It can be seen that ΔH_r of the isodesmic reaction is negative for compound 5 ($\Delta H_r = -18.243$ kcal mol^{-1}) and positive for the enol counterpart 6 ($\Delta H_r = 3.337$ kcal mol^{-1}). This indicates that enol 6 is more stable than ketone 5.

Effect of the CF_3 group

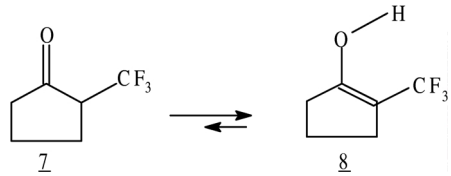
The CF_3 substituent also acts as electron withdrawing group which increases the acidity of H1 (compound 7) and hence facilitates formation of the enol (8).

This is supported by the calculation of ΔG_r (Table 7) for the keto-enol system, which was found to be -10.361 kcal mol^{-1}.

The stabilization effect of the CF_3 group on the ketone and its enol counterpart is given in Table 8.



7 8



7 8

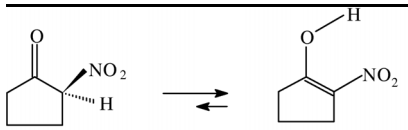
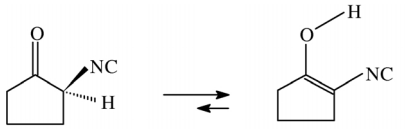
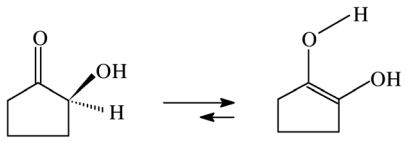
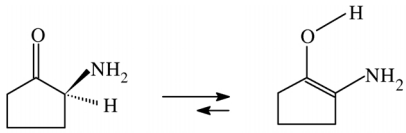
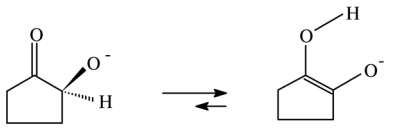
ΔH_r of the isodesmic reactions is negative for ketone ($\Delta H_r = -9.552$ kcal mol^{-1}) and positive for enol ($\Delta H_r = 6.034$ kcal mol^{-1}), which indicates that the enol 8 is stabilized and the ketone 7 is destabilized by the CF_3 group.

Effect of the CN group

The CN substituent in compound 9 decreases slightly the electron density on C2 and increases it slightly on C1 and C3 when compared to the electron densities of the parent compound 1 (Table 3), i. e. behaves as a weakly electron releasing.

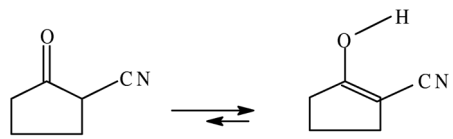
In the case of enol 10, the CN substituent decreases the electron density on C1 and increases it

Table 7. Thermodynamic properties of monosubstituted keto-enol systems.

Keto-Enol System	ΔH_r (kcal mol^{-1})	ΔS_r ($\times 10^{-3}$ kcal mol^{-1}K^{-1})	ΔG_r (kcal mol^{-1})
 5 6	−16.46	2.342	−17.16
7 8	−10.466	−0.352	−10.361
9 10	− 3.1	−0.953	− 2.82
 11 12	− 4.45	−1.086	− 4.126
 13 14	− 1.109	7.905	− 3.446
 15 16	− 2.793	4.682	− 4.189
 17 18	−37.849	2.429	−38.57

on C3, which indicates that the CN group behaves as electron withdrawing when attached to a system with high electron density (in this case C=C bond), and as electron releasing when attached to a system with low electron density (such as C-C bond). In other words, the CN group behaves according to electron demand [16 – 21] i.e. it shows amphielectronic behavior.

Thermodynamic calculations of ΔG_r (Table 7) for cyano substituted keto-enol systems with a small neg-

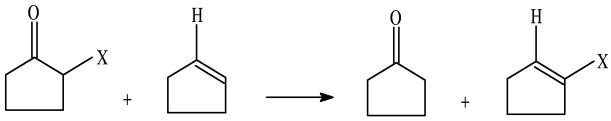


9 10

ative value ($\Delta G_r = -2.82$ kcal mol^{-1}) indicate that the reaction is slightly spontaneous.

This is supported by the stabilization effect of CN group on both the ketone and its enol counterpart (Ta-

Table 8. Evaluation of substituent effects on cyclopentanone and its enol counterpart (ΔH_r in kcal/mol).

	NO_2	CF_3	CN	NC	OH	NH_2	O^-
	−18.243	−9.550	−7.531	−10.869	−17.381	−13.962	4.888
	3.337	6.034	0.659	−1.299	−7.973	−6.049	47.827

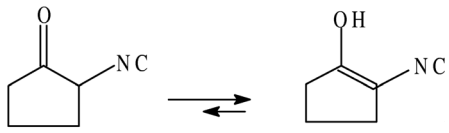
ble 8) using the isodesmic reaction. It can be seen that compound 9 is destabilized by the CN group ($\Delta H_r = -7.531$ kcal mol^{-1}) while the compound 10 is very slightly stabilized by the CN group ($\Delta H_r = 0.659$ kcal mol^{-1}). This clearly shows that the shift in equilibrium is a result of the destabilization of the ketone from one side and slightly the stabilization of the enol from the other side.

Effect of the NC group

Also the NC group behaves as a weakly electron-releasing group in compound 11 (ketone) similar to the CN group.

In case of compound 12 (enol), the NC substituent at C2 shows an amphielectronic behavior, similar to the CN group.

Calculation of the Gibbs energy (ΔG_r) of the NC substituted keto-enol system (Table 7) shows that $\Delta G_r = -4.126$ kcal mol^{-1}, which means that the reaction is slightly spontaneous.

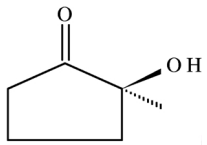


11 12

This result is supported by the isodesmic reaction (Table 8). It can be seen that ΔH_r for the isodesmic reactions of 11 and 12 are negative ($\Delta H_r = -10.869$ kcal mol^{-1} for 11 and 12, $\Delta H_r = -1.299$ kcal mol^{-1}for 12). From these two values, compound 12 is less destabilized by the NC than compound 11. This explains the shift in the equilibrium to enol side.

Effect of the OH group

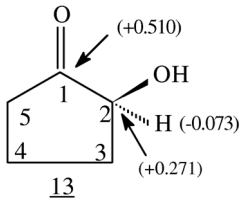
It was found that the OH group decreases the electron density at C2 and increases it at the adjacent carbon atoms (C1 and C3) and H1, when compared



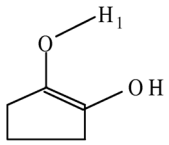
13

with the parent 1 (Table 3), i. e it behaves as electron releasing.

From the charge distribution of compound 13 it is shown that the carbonyl group will be destabilized due to electronic repulsion between C1 and C2 (which both carry positive charges) [10]. This means that the ketone 13 will be destabilized, and this may give a good motive for the enol formation 14.



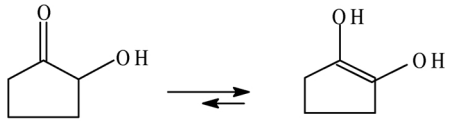
13



14

The stability of enol 14 could be a result of the delocalization of the electron density through interaction between the C=C bond and the OH group [22] which is reflected by the change in geometrical parameters of enol 14. It is noticed from Table 6 that there is an increase in the C1=C2 bond length and a decrease in <C1C2O and <C5C1C2 when compared with parent 2 (Table 2).

This is confirmed by thermodynamic calculation of the Gibbs free energy (ΔG_r) of the OH substituted keto-enol system (Table 7).



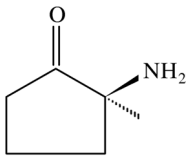
13 14

It was found that ΔG_r has a small negative value ($\Delta G_r = -3.466$ kcal mol^{-1}), which means that the reaction is slightly spontaneous.

This stabilization is also confirmed by the isodesmic reaction (Table 8). It can be seen that ΔH_r values of the isodesmic reactions of both 13 and 14 are negative ($\Delta H_r = -17.381$ kcal mol^{-1} for 13 and $\Delta H_r = -7.973$ kcal mol^{-1} for 14). From these values it is clearly seen that both 13 and 14 are destabilized by the OH group, but 14 is less so, which explains the shift in the equilibrium to the enol side. This agrees with the small negative value of ΔG_r.

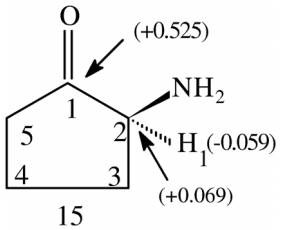
Effect of the NH_2 group

Also NH_2 behaves as an electron-releasing group; this is reflected by a decrease in the electron density at C2 (at which the substituent is attached) and an increase in the electron densities at the adjacent carbon atoms (C1 and C3) and at H1, when compared with the parent (Table 3).



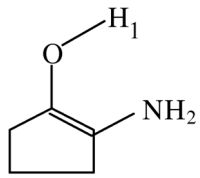
15

From the charge distributions of compound 15, it can be seen that the carbonyl group will be destabilized due to electrostatic repulsion between C1 and C2 (which both carry positive charges) [10].



15

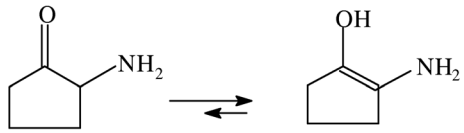
This means that ketone 15 will be destabilized and has a tendency to form enol 16.



16

The stability of enol 16 could also be a result of delocalization of the electron density through interaction between the C=C bond and the NH_2 group [22] which is reflected by an increase in the C1=C2 bond length and a decrease in the angles <C5C1C2 and <OC1C2 (Table 6) when compared to those of the parent 2 (Table 2).

This stability is confirmed by the thermodynamic calculation (Table 7) of ΔG_r of the NH_2 substituted keto-enol system, which shows that ΔG_r has a small negative value ($\Delta G_r = -4.189$ kcal mol^{-1}). This indicates that the reaction is spontaneous, but not to a high degree.



15 16

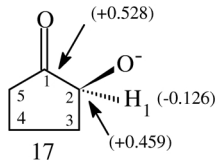
Also this result of stabilization is supported by the isodesmic reaction (Table 8). It can be seen that the ΔH_r values for the isodesmic reactions of both 15 and 16 are negative ($\Delta H_r = -13.962$ kcal mol^{-1} for 15 and $\Delta H_r = -6.049$ kcal mol^{-1} for 16). This indicates that both 15 and 16 are destabilized by the NH_2 group, but 16 is less destabilized so (less negative value). This suggests that the shift in equilibrium is to the enol side, in good agreement with calculated ΔG_r value which predicts a small shift in equilibrium to the enol side.

Effect of O^-

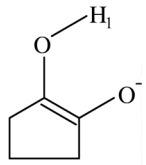
Introduction of an O^- substituent at C2 of compound 17 causes a high decrease in <C1C2C3 accompanied with a very large increase in C1-C2 (1.687 Å) and a small increase in C2-C3 (1.542 Å) (Table 6), when compared with the parent 1 (Table 2). Also a decrease in C1=O from 1.203 Å in the parent 1 to 1.181 Å in 17 was found, which suggests an increase in conjugation. Hence the stability of the carbonyl carbon may increase slightly.

The O^- substituent behaves as a strong electron releasing group; this is reflected by a decrease in the electron density at C2 and an increase at the adjacent carbon atoms (C1 and C3) and the H1 atom, when compared with the parent 1 (Table 3).

From the charge distributions of compound 17 it is shown that the carbonyl will be destabilized due to electrostatic repulsion between C1 and C2 (which both carry positives charges) [10], and has a tendency to form enol 18.



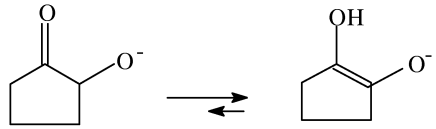
17



18

The stability of enol 18 could be a result of the delocalization of the electron through interaction between C1=C2 and the O^- substituent; this is reflected by a change in the geometrical parameters of 18. It is noticed from Table 6 that there is a large decrease in the angle C1C2C3 accompanied by large increase in C1=C2 (1.478 Å), increase in C2-C3 and a decrease in C1-O when compared with the parent 2 (Table 2).

The stability of the O^- substituted keto-enol system was studied by calculation of ΔG_r (Table 7), which was found to have a high negative value ($\Delta G_r = -38.57$ kcal mol^{-1}). This means that the reaction is highly spontaneous and shifts the equilibrium to the enol side.



17 18

This suggestion is confirmed by using the isodesmic reaction. It can be seen from Table 8 that ΔH_r for the isodesmic reactions of both 17 and 18 is positive ($\Delta H_r = 4.888$ kcal mol^{-1} for 17 and $\Delta H_r = 47.827$ kcal mol^{-1} for 18). This clearly shows that the O^- group stabilizes both 17 and 18, but 18 is much more stabilized. This explain the high shift in the equilibrium ($\Delta G_r = -38.57$ kcal mol^{-1}) to enol side.

Conclusion

It was found that ketone is more stable than the enol counterpart. The perfluorination destabilized ketone (shift to the enol side) agrees better with the experimental results than ab initio calculations. It agrees with density function calculations. In fact, the shift in equilibrium toward the enol side is attributed to the ketone destabilization and not to the enol stabilization. All substituents have some effects on the geometrical parameters, and this is most pronounced in the case of the O^- substituent. Almost all substituents are destabilizing ketone to a certain extent, except O^-, which slightly stabilizes ketone, while the groups NO_2, CF_3 and O^- stabilize enol.

[1] J. E. Dubois, M. El-Alaoui, and J. Toullec, J. Amer. Chem. Soc. **103**, 5393 (1980).
[2] (a) N. S. Isaacs, "Physical Organic Chemistry", Longman (1990); (b) I. Fleming, Chemia **34**, 265 (1980).
[3] P. E. Lindner and D. M. Lemal, J. Org. Chem. **61**, 5109 (1996).
[4] Y. Kwon, J. Mol. Struct. (Theochem) **488**, 93 (1999).
[5] (a) S. M. Khalil and M. Shanshal, Theor. Chem. Acta **46**, 23 (1977); (b) S. M. Khalil and H. M. Jarjis, Z. Naturforsch. **46a**, 898 (1991); (c) N. M. Yahya and S. M. Khalil, ibid **47a**, 768 (1992); (d) A. G. Abed and S. M. Khalil, ibid **54a**, 251 (1999).
[6] R. C. Bingham, M.J. S. Dewar, and D. H. Lo, J. Amer. Chem. Soc. **97**, 1285 (1975).
[7] B. A. Murtagh and R. W. Sargent, Comp. J. **13**, 185 (1970).
[8] P. Pulay, Mol. Phys. **17**, 197 (1969).
[9] D. A. Dixon and B.E. Smart, J. Phys. Chem. **95**, 1609 (1991).
[10] N. Heinrich, W. Koch, G. Frenking, and H. Schwarz, J. Amer. Chem. Soc. **108**, 593 (1986).
[11] J. R. Keefee, A. J. Kresge, and N. P. Schepp, J. Amer. Chem. Soc. **112**, 4862 (1990).
[12] Y. Chiang, M. Hajatti, J. R. Keefee, and et al., J. Amer. Chem. Soc. **109**, 4000 (1987).
[13] W. H. Hehre, R. Ditchfield, L. Radom, and J. A. Pople, J. Amer. Chem. Soc. **92**, 4796 (1970).
[14] M. H. Lien and A. C. Hopkinson, J. Phys. Chem. **88**, 1513 (1984).
[15] S. M. Khalil and H. M. Jarjis, Z. Naturforsch. **42a**, 761 (1987).

[16] S. M. Khalil and H. M. Jarjis, Z. Naturforsch. **46a**, 247 (1990).
[17] H. M. Jarjis and S. M. Khalil, J. Chem. Soc. Perkin Trans. **2**, 17019 (1986).
[18] W. F. Reynolds, P. Dais, R. W. Taft, and R. D. Topsom, Tetrahedron Letters **22**, 1795 (1981).
[19] R. G. Gassman and J. J. Talley, J. Amer. Chem. Soc. **102**, 1214 (1980).
[20] D. A. Dixon, P. A. Charlier, and R. G. Gassman, J. Amer. Chem. Soc. **102**, 3957 (1980).
[21] M. N. Paddon-Row, C. Santiago, and K. W. Houk, J. Amer. Chem. Soc. **102**, 6561 (1980).
[22] C. C. Su, C. K. Lin, and C. C. Wu, J. Phys. Chem. A **103**, 3289 (1999).