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THERMODYNAMICS OF ELECTRON TRANSFER PROCESSES IN LIQUID AND GAS PHASES. 1. CORRELATIONS OF ELECTROOXIDATION AND IONIZATION POTENTIALS WITH SUBSTITUENT CONSTANTS FOR SOME INDOLE AND INDOLIZINE DERIVATIVES: QUANTITATIVE SOLVATION FREE ENERGIES

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ABSTRACT

A linear regression analysis of the oxidation processes of some 1-methyl 2-phenyl 3-substituted indoles and 2-phenyl 1,3-disubstituted indolizines in acetonitrile, compared with the ionization processes of the same compounds in the gaseous phase is presented. In this analysis total standard deviation, slope and intercept standard deviations, correlation coefficient, null hypotheses, $a = 0$, $b = 0$, $b = 1$, $b_1 = b_2$ (where a is the intercept and b the slope of the regression equation), and the Student t-test for the above cited values were taken into account. A thermodynamic cycle was used to calculate the molecule and cation solvations.

For both series of compounds the following correlations were critically examined for the electron transfer process:

(i) ionization potentials vs. oxidation potentials or substituent constants;
(ii) solvation free energies vs. ionization potentials;
(iii) oxidation potentials vs. substituent constants.

These relations provide evidence that there is good correlation between the gas and liquid phases with the exception of the two Me, N_2Ph isomers in the indolizine series. Again it was found that the solvation effect causes no departures from linear energy correlations of gas vs. thermodynamic properties.

Finally, a comparison of the reaction constants shows that for the same series the change due to the medium (liquid–gas phases) is not reflected in a variation of the reaction constant; but for different series, the reaction constants are different from each other, thus showing a different mechanism of reaction.

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INTRODUCTION

It is well-known that solvation factors play an important role in determining the course of reactions in the liquid phase [1–8].

Some recent developments in gas-phase chemistry [9–13] allow quantitative solvation energies to be evaluated in the most general organic chemical reactions, i.e. proton transfer processes. Indeed, techniques such as ion cyclotron resonance (ICR), high-pressure mass spectrometry (HPMS) and flowing afterglow (FA), allow gas-phase proton transfer to be related to solution processes.

Isodesmic (ion–molecule) proton transfers, such as

$$A_1H + A_2^- = A_1^- + A_2H \tag{1}$$

$$B_1H^+ + B_2 = B_1 + B_2H^+ \tag{2}$$

are usually employed to account for the differential effect of structural changes on energy differences both in liquid and gas phases for many substituted acids and bases.

Hepler and co-workers [14–17] have stressed the usefulness of expressing thermodynamic functions of reactions like (1) and (2) in terms of "external" and "internal" contributions:

$$\delta\Delta G = \delta\Delta G_{\text{in}} + \delta\Delta G_{\text{ex}}$$

"Internal" effects are those intrinsic to the molecules and to the ions, whereas "external" ones are derived from solvent interactions with the molecules and ions.

To separate the solvent effect from the intrinsic effect in eqns. (1) and (2) it is necessary to know the thermodynamics for both the liquid and gas phases. The thermodynamic cycle used to calculate the "external" interactions could be the following scheme where aniline (B_1) is used as a reference compound for a series of substituted anilines (B_2)

$$\begin{tikzcd}
B_1H^+(g) \arrow[d] & {+\,B_2(g)} \arrow[d] \arrow[r, "\delta\Delta P_i(g)"] & B_1(g) \arrow[d] & {+\,B_2H^+(g)} \arrow[d, "\Delta P_s"] \\
B_1H^+(x) & {+\,B_2(x)} \arrow[r, "\delta\Delta P_i(x)"] & B_1(x) & {+\,B_2H^+(x)}
\end{tikzcd}$$

so the following can be written:

$$\delta\Delta P_i(x) - \delta\Delta P_i(g) = [\Delta P_s(B_1) - \Delta P_s(B_1H^+)] - [\Delta P_s(B_2) - \Delta P_s(B_2H^+)] \tag{3}$$

and again

$$\delta\Delta P_i(x) - \delta\Delta P_i(g) = \delta\Delta P_s^{g\to x} \tag{4}$$

where $\delta\Delta P_i(g)$ will be the gaseous phase change of any thermodynamic property ($P_i = G, H, S$) from B_1 to B_2. The corresponding value in solvent

x is $\delta\Delta P_{\mathrm{i}}(x)$. The right-hand term of eqn. (4) can be assumed as the proton transfer in solvent x, which refers to a gaseous initial thermodynamic state, i.e., $\delta\Delta P_{\mathrm{s}}^{\mathrm{g}\to x} = \delta\Delta P_{\mathrm{i}}^{\mathrm{g}\to x}$. Again it can be assumed that the $\delta\Delta P_{\mathrm{i}}^{\mathrm{g}\to x}$ term is a measure of the "external" interactions so that it is reasonable to assume that in the equation:

$$\delta\Delta P_{\mathrm{i}}(x) = \delta\Delta P_{\mathrm{i}}(\mathrm{g}) + \delta\Delta P_{\mathrm{i}}^{\mathrm{g}\to x} \tag{5}$$

the $\delta\Delta P_{\mathrm{i}}(x)$ term represents the total interactions, $\delta\Delta P_{\mathrm{i}}(\mathrm{g})$ the "internal" interactions and $\delta\Delta P_{\mathrm{i}}^{\mathrm{g}\to x}$ the "external" ones.

A rule may be applied to solvation energies: for an isodesmic ion–molecule reaction the difference between thermodynamic properties in solution and in the gas phase lies in the different effects of the molecule's structure (charge distribution through resonance, hydrogen bonding, polarization) on the solvation properties, $\delta\Delta P_{\mathrm{i}}^{\mathrm{g}\to x}$, of the uncharged molecules and ions. So the differential solvation factors are assumed to be those which cause departures from a linear relationship of gas-phase vs. solution thermodynamic properties.

Even for electron-transfer processes the comparison between thermodynamic parameters in the liquid phase, especially half-wave oxidation (or reduction) potentials, $E_{1/2}$, and thermodynamic parameters in the gas phase, such as ionization potentials, IP (or electron affinities, EA), allows the evaluation of the solvation factors involved.

Indeed, for a one-electron, reversible-oxidation process related to a series of substituted compounds, R–Y, bearing the same oxidizable group R and differing only in the nature of the substituent Y, the following thermodynamic cycle can be written:

$$\begin{tikzcd}
\mathrm{R{-}H^{+\bullet}(g)} \arrow[d] & + & \mathrm{R{-}Y(g)} \arrow[d] \arrow[rr, "\delta\Delta P_{\mathrm{ox}}(\mathrm{g})"] & & \mathrm{R{-}H(g)} \arrow[d] & + & \mathrm{R{-}Y^{+\bullet}(g)} \arrow[d, "\Delta P_{\mathrm{s}}"] \\
\mathrm{R{-}H^{+\bullet}}(x) & + & \mathrm{R{-}Y}(x) \arrow[rr, "\delta\Delta P_{\mathrm{ox}}(x)"] & & \mathrm{R{-}H}(x) & + & \mathrm{R{-}Y^{+\bullet}}(x)
\end{tikzcd}$$

in which $\delta\Delta P_{\mathrm{ox}}(\mathrm{g})$ and $\delta\Delta P_{\mathrm{ox}}(x)$ represent, for example, the difference in IP and $\delta\Delta E_{1/2}$ values, respectively, for the unsubstituted R–H (chosen as a reference) and the substituted R–Y compounds. Thus, the equation can be written as:

$$\delta\Delta P_{\mathrm{ox}}(x) - \delta\Delta P_{\mathrm{ox}}(\mathrm{g}) = \delta\Delta P_{\mathrm{s}}^{\mathrm{g}\to x}$$

where the right-hand term is assumed to be the difference between the $E_{1/2}$ values of the two redox couples, which refers to a gaseous initial thermodynamic state, so that $\delta\Delta P_{\mathrm{s}}^{\mathrm{g}\to x} = \delta\Delta P_{\mathrm{ox}}^{\mathrm{g}\to x}(x)$. This term may represent the "external" interactions, i.e. the difference between the molecule and radical cation solvations. An analogous scheme could also be written for a one-electron reversible reduction process in which the two redox couples

$R-H/R-H^{\dot{-}}$ and $R-Y/R-Y^{\dot{-}}$ are involved. So even for the radical ion–molecule reaction the differential solvation factors can be assumed as those which cause departures from a linear relationship of gas-phase vs. liquid thermodynamic properties.

Some linear energy relationships between oxidation (or reduction) $E_{1/2}$, IP (or EA), highest occupied molecular orbitals (HOMO) or lowest unoccupied molecular orbitals (LUMO) σ-substituent constants have been reported [18–24]. Unfortunately, in most of these relations it is assumed that the closer the value of r (correlation coefficient) to unity, the better the fit of the results. But one must consider that the r value is only a guide to the significance of any apparent correlation between two random variables. It is then interesting to use linear regression analysis which supplies the precise form of the mathematical function relating to the two variables and tests how the experimental results support the theoretical relationship within the limits of the experimental error of the measurements. In this context, more useful tests are the standard deviation on the slope and on the intercept, the total standard deviation, and the Student t-test for the intercept, slope and the correlation coefficient values of the linear regression [25–30].

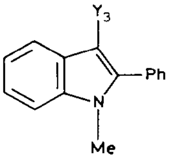
The aim of this work is to compare, through a linear regression analysis, the oxidation process in the liquid (x = MeCN) and in the gas phases for a number of indole and indolizine derivatives and to gather reliable information from the statistical point of view about the electron-transfer mechanism in the liquid and gas phases. A further purpose of this paper is to obtain simple equations which are useful in predicting some thermodynamic properties (namely oxidation and, ionization potentials, substituent constant values, solvation free energies) for 1-methyl 2-phenyl 3-substituted indoles and for 2-phenyl 1,3-disubstituted indolizines.

EXPERIMENTAL AND PROCEDURE

The preparation of the indole (**1**–**15**) and indolizine (**16**–**27**) derivatives and the techniques used for determining the IP and $E_{1/2}$ values have been previously described [31]. The half-wave oxidation potentials, $E_{1/2}$ were obtained in 0.1 M Et_4-$NClO_4$-MeCN using a pulsed platinum disc and $Ag/AgClO_4$ (0.1 M in MeCN) as working and reference electrodes, respectively. All the compounds examined exhibited a "quasi-reversible" charge transfer as tested by cyclic voltammetric experiments. A programme which supplies a linear regression analysis with total standard deviation, slope and intercept deviations, correlation coefficient and null hypotheses, $a = 0$, $b = 0$, $b = 1$ and $b_1 = b_2$ (where a is the intercept and b the slope of the regression equation), and the Student t-test for all the above values was run on an Olivetti M20st computer.

RESULTS AND DISCUSSION

Tables 1 and 2 list the $\delta\Delta E_{1/2}$ (V), $\delta\Delta$IP (eV), $\delta\Delta G_{\text{ox}}^{g\rightarrow x}$ (kJ mol^{-1}), $\delta\Delta G_{\text{ox}}$(g) (kJ mol^{-1}), σ_m and σ_o values for the indole (**1–15**) and indolizine (**16–21**) series. For the latter, $\Sigma\sigma$ values due to the sum of the *ortho* and *meta* substituent effects are also given. From these values the following correlations were critically examined, by means of a linear regression analysis, for both the series: (i) $\delta\Delta$IP vs. $\delta\Delta E_{1/2}$, (ii) $\delta\Delta G_{\text{ox}}^{g\rightarrow x}$ vs. $\delta\Delta G_{\text{ox}}$(g), (iii) $\delta\Delta E_{1/2}$ vs. σ_m (or $\Sigma\sigma$), (iv) $\delta\Delta$IP vs. σ_m (or $\Sigma\sigma$). For all these correlations the null hypotheses considered were;



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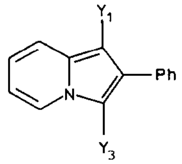

16 – 27

(1) for the intercept $a = 0$;

(2) for the slope $b = 0$ and $b = 1$;

(3) for the correlation coefficient $r = 0$.

Furthermore for (iii) and (iv) the null hypothesis is $b_1 = b_2$ where slopes of the two different series in the same medium or slopes of the single series in

TABLE 1

Differences with respect to unsubstituted compound **10** of the oxidation and ionization potentials, solvation free energy, ionization free energy for 1-methyl 2-phenyl 3-substituted indoles plus *meta* substituent values

Compound	Y_3	$\delta\Delta E_{1/2}$ (V)	$\delta\Delta$IP (eV)	$\delta\Delta G_{\text{ox}}$(g) (kJ mol^{-1})	$\delta\Delta G_{\text{ox}}^{g\rightarrow x}$ (kJ mol^{-1})	σ_m
1	MeC=CHMe	−0.220	−0.33	−31.84	53.07	−0.07 [b]
2	MeC=CH_2	−0.130	−0.13	−12.54	25.09	0.003 [b]
3	SMe	−0.130	0.00	0.00	12.54	0.14 [b]
4	Me	−0.095	−0.15	−14.47	23.64	−0.07 [a]
5	CH_2Ph	−0.065	−0.16	−15.44	21.71	0.04 [a]
6	CH_2OH	0.010	0.13	12.54	−13.51	0.12 [b]
7	CH(OH)Ph	0.035	0.01	0.96	−4.34	0.14 [b]
8	SPh	0.025	0.01	0.96	−3.38	0.13 [b]
9	N_2Ph	0.050	0.03	2.89	−7.72	0.16 [b]
10	H	0.000	0.00	0.00	0.00	0.00
11	NO	0.080	0.06	5.79	−13.51	0.18 [b]
12	Cl	0.120	0.06	5.79	−17.37	0.37 [a]
13	CHO	0.440	0.50	48.24	−90.70	0.38 [a]
14	COMe	0.315	0.30	28.94	−59.34	0.38 [a]
15	NO_2	0.645	0.73	70.43	−132.67	0.71 [a]

[a] Values from ref. 32.

[b] Values calc. by us.

TABLE 2

Differences with respect to unsubstituted compound **22** of the oxidation and ionization potentials, solvation free energy, ionization free energy for 2-phenyl 1,3-disubstituted indolizines, plus $\Sigma\sigma$, *meta* and *ortho* substituent values

Compound	Y_1	Y_3	$\delta\Delta E_{1/2}$ (V)	$\delta\Delta$IP (eV)	$\Delta G_{ox}(g)$ (kJ mol^{-1})	$\Delta G_{ox}^{g\to x}$ (kJ mol^{-1})	σ_m	σ_o	$\Sigma\sigma$
16	H	Me	−0.185	−0.08	−7.72	25.57	0.00	−0.13 [a]	−0.13
17	SMe	Me	−0.165	−0.09	−8.68	24.60	0.14 [a]	−0.13 [a]	0.01
18	SPh	Me	−0.090	−0.15	−14.47	23.16	0.13 [b]	−0.07 [b] −0.13 [a]	0.06 [b]
19	N_2Ph	Me	−0.075	−0.27	−26.05	33.29	0.16 [b]	−0.06 [b] −0.13 [a]	0.10 [b]
20	COMe	Me	0.140	0.10	9.65	−23.16	0.38 [a]	−0.13 [a]	0.25
21	CHO	Me	0.210	0.23	22.19	−42.45	0.38 [a]	−0.13 [a]	0.25
22	H	H	0.000	0.00	0.00	0.00	0.00	0.00	0.00
23	Me	H	−0.180	−0.03	−2.89	20.26	−0.07 [a]	0.00	−0.07
24	Me	SPh	−0.055	−0.15	−14.47	19.78	−0.07 [a]	0.22 [c]	0.15 [b]
25	Me	N_2Ph	−0.040	−0.30	−28.95	32.80	−0.07 [a]	0.25 [c]	0.18 [b]
26	Me	COMe	0.170	0.15	14.47	−30.88	−0.07 [a]	1.06 [a]	0.99
27	Me	CHO	0.250	0.27	26.05	−50.17	−0.07 [a]	1.02 [a]	0.95

[a] Values from ref. 32.

[b] Values calc. by us.

[c] Values calc. by using $\Sigma\sigma$.

different media are compared. This is a very important statistical comparison in organic chemical physics when small variations of Hammett's reaction constant, ρ, were studied as a function of the medium variation. For the Hammett equation the regression was not forced through the origin. An intercept was drawn with the least-squares treatment, but it was normally indistinguishable from zero. The null hypotheses were tested by using the Student t-test. The t values of a, b and r were calculated by means of the expressions:

$$t_a = (a - A)/S_a$$

$$t_b = (b - B)/S_b$$

$$t_b(1,2) = (b_1 - b_2 - A)/S(b_1 - b_2)$$

$$t_r = |r| \cdot [(n-2)/(1-r^2)]^{1/2}$$

(where $A = 0$, $B = 0$, or 1, and S_a and S_b are the standard deviations of a and b) and were compared with those of a set of t-tables. If $t > t_{\mathrm{CL},n-2}$ where $n - 2$ is the degree of freedom and CL the confidence level for significance of the regression, then for CL < 0.95 the null hypothesis is accepted (chemical hypothesis) while for CL > 0.999 its rejection is highly significant.

(i) $\delta\Delta IP$ vs. $\delta\Delta E_{1/2}$

For the indole series (see Table 3) it can be seen that between the two variables there is a highly significant relation. The coefficient regression (slope) is equal to 1.11, i.e. the substituent effect on the free energy is very similar in the gas phase and in acetonitrile. There is a small attenuation of the substituent effect from the gas to the liquid phases. For the indolizine

TABLE 3

Linear regression of $\delta\Delta$IP vs. $\delta\Delta E_{1/2}$ for indole and indolizine series

	Indoles	Indolizines	Indolizines [a]
n	15	12	10
Intercept	−0.01	−0.02	0.02
Slope	1.11	0.91	0.81
SD of intercept	0.02	0.03	0.02
SD of slope	0.08	0.24	0.14
SD of regression	0.07	0.12	0.07
r	0.97	0.77	0.89
NH: intercept = 0	CL < 0.95	CL < 0.95	CL < 0.95
NH: slope = 0	CL > 0.999	0.99 < CL < 0.999	CL > 0.999
NH: slope = 1	CL < 0.95	CL < 0.95	CL < 0.95
NH: $r = 0$	CL > 0.999	0.99 < CL < 0.999	CL > 0.999

[a] Without compound **19** ($Y_1 = N_2Ph$, $Y_3 = Me$) and **25** ($Y_1 = Me$, $Y_3 = N_2Ph$).

n = number of points; SD = standard deviation; r = correlation coefficient; NH = null hypothesis; CL = confidence level.

series (Table 3) the linear relation is significant. It becomes highly significant if the two isomers **19** (N_2Ph, Me) and **25** (Me, N_2Ph) are removed from the set. It is noteworthy that the correlation coefficient values increase from 0.77 to 0.89. As r gives the fraction of variation of the independent variable, which is explained by the regression equation, when $r = 0.77$ the equation covers about 59% of the fraction, while for $r = 0.89$ this value becomes 80%.

It is also well known that the successive elimination of data points tends to increase the value of r unless some of the points show substantial deviations. To find out to what extent the greater precision of the modified set is merely due to the smaller number of data, the t values were compared with values corresponding to an acceptable standard level, say 1%, through the equation $C = t_{1\%}/t$. The smaller value of the modified set (0.596) with respect to that of the non-modified one (0.825) confirms that the greater precision as measured by r is not solely due to a smaller number of data. There is also evidence that the substituent effects of two (Me, N_2Ph) isomers (**19** and **25**) influence the free energy in the gas and liquid phases in a different way.

Furthermore, the slopes of the two series are not significantly different from each other, showing similar trends for the two series.

(ii) $\delta\Delta G_{ox}^{g\rightarrow x}$ *vs.* $\delta\Delta G_{ox}(g)$

It is usually hypothesized that a linear correlation between $E_{1/2}$ and IP is to be expected if the free energy of solvation is constant within a series of compounds or if there is an approximately linear function between free-en-

TABLE 4

Linear regression of $\delta\Delta G_{ox}(x)$ vs. $\delta\Delta G_i(g)$ for indole and indolizine series

	Indoles	Indolizines
n	15	12
Intercept	−1.18	−1.52
Slope	−1.84	−1.65
SD of intercept	1.54	2.93
SD of slope	0.06	0.17
SD of regression	5.77	10.02
r	0.99	−0.95
NH: intercept = 0	CL < 0.95	CL < 0.95
NH: slope = 0	CL > 0.999	CL > 0.999
NH: slope = 1	CL > 0.999	CL > 0.999
NH: $r = 0$	CL > 0.999	CL > 0.999

n = number of points; SD = standard deviation; r = correlation coefficient; NH = null hypothesis; CL = confidence level.

ergy of solvation and ionization potential. Table 4 shows that for the indole and indolizine series there are two highly significant correlations. This fact confirms the goodness of the fit (GOF) between the gas and liquid phases.

So it can be noted that, in this case, there are no differential solvation factors which cause departures from linear energy correlations of gas vs. thermodynamic properties.

(iii) $\delta\Delta E_{1/2}$ *vs.* σ_m *(or* $\Sigma\sigma$*)*

This linear regression gives prominence to substituent effects.

For eight indole derivatives (Table 1), for which the substituent constant, σ_m, values of the corresponding benzoic acid derivatives are reported in the literature [32], a significant linear correlation of $\delta\Delta E_{1/2}$ vs. σ_m was found (Table 5). The reaction constant ρ_1(MeCN) shows a value (0.98) which is not significantly different, from the statistical point of view, from unity.

As it is well known, in a linear regression analysis of the equation $y = f(x)$, it is incorrect to use the regression parameters, calculated using y as a dependent and x as an independent variable, to obtain an x' value (dependent) from $y = Y$ (independent). Thus from the linear regression equation obtained by reversing the variables (i.e. σ_m vs. $\delta\Delta E_{1/2}$, the substituent constant, σ_m, values for the remaining seven indoles were calculated (Table 1). The substituent effect values for the indolizine series were calculated in the following way: if the additivity principle [33–35] is assumed, the $\Sigma\sigma$ values will be equal to the sum of the *meta* (σ_m) and *ortho* (σ_o) substituent effects. A set of seven (indolizine) derivatives, for which the σ_m and σ_o values are available in the literature (Table 2), shows a significant linear relation ($\delta\Delta E_{1/2}$ vs. $\Sigma\sigma$) (see Table 5). The reaction constant value,

TABLE 5

Linear regression of $\delta\Delta E_{1/2}$ vs. σ_m for indole and of $\delta\Delta E'_{1/2}$ vs. $\Sigma\sigma_m$ for indolizine series

	Indoles	Indolizines
n	8	7
Intercept	−0.08	−0.09
Slope	0.98	0.33
SD of intercept	0.06	0.04
SD of slope	0.18	0.08
SD of regression	0.13	0.10
r	0.91	0.87
NH: intercept = 0	CL < 0.95	CL < 0.95
NH: slope = 0	0.99 < CL < 0.999	0.99 < CL < 0.999
NH: slope = 1	CL < 0.95	CL > 0.999
NH: $r = 0$	0.99 < CL < 0.999	0.99 < CL < 0.999

n = number of points; SD = standard deviation; r = correlation coefficient; NH = null hypothesis; CL = confidence level.

ρ_2(MeCN) = 0.33, differs significantly from unity. Incidentally, a comparison between the reaction constants, ρ_1(MeCN) and ρ_2(MeCN), is possible by means of the expressions $t_b = (b_1 - b_2 - A)/S_b(b_1 - b_2)$, if it could be verified that the standard errors of the two series are not statistically different [25]. The difference between the two values, ρ_1(MeCN) = 0.97 and ρ_2(MeCN) = 0.33, shows an uncertain degree of significance ($0.95 < \mathrm{CL} < 0.99$). This implies that the influence of the substituents on the two reaction mechanisms could not be similar.

Again, by reversing the variables (i.e. $\Sigma\sigma$ vs. $\delta\Delta E_{1/2}$) the values for four indolizine derivatives were found (Table 2). Furthermore, using the expression $\Sigma\sigma = \sigma_m + \sigma_o$, the σ_o values for two *ortho* substituent groups were calculated. Finally, in the liquid phase, none of the compounds of the two series show a behaviour which deviates much from linearity, with the exception of compound **21** (CHO, Me) which is removed from the indolizine series.

(iv) $\delta\Delta IP$ vs. σ_m (or $\Sigma\sigma$)

A linear correlation between $\delta\Delta$IP and σ_m or $\Sigma\sigma$ allows the effect of the substituents on the "intrinsic" thermodynamic properties to be studied and compared with that occurring in a solution. For the first series, a set of eight points again gives a significant linear regression (Table 6). The ρ_1(g) value (1.11) is not significantly different from the value, ρ_1(MeCN) (0.97), of the reaction constant in the liquid phase ($\mathrm{CL} < 0.95$). So it could be concluded that the change due to the medium is not reflected by a variation of the reaction constant. For the second series there is a significant linear regression (Table 6) for a set of seven points, again if compound **21** (CHO, Me) is

TABLE 6

Linear regression of $\delta\Delta$IP vs. σ_m for indole and of $\delta\Delta$IP vs. $\Sigma\sigma_m$ for indolizine series

	Indoles	Indolizines
n	8	7
Intercept	−0.11	−0.03
Slope	1.12	0.25
SD of intercept	0.07	0.03
SD of slope	0.20	0.05
SD of regression	0.14	0.06
r	0.91	0.91
NH: intercept = 0	$\mathrm{CL} < 0.95$	$\mathrm{CL} < 0.95$
NH: slope = 0	$0.99 < \mathrm{CL} < 0.999$	$0.99 < \mathrm{CL} < 0.999$
NH: slope = 1	$\mathrm{CL} < 0.95$	$\mathrm{CL} > 0.999$
NH: $r = 0$	$0.99 < \mathrm{CL} < 0.999$	$0.99 < \mathrm{CL} < 0.999$

n = number of points; SD = standard deviation; r = correlation coefficient; NH = null hypothesis; CL = confidence level.

removed. The $\rho_2(g)$ value (0.25) is not significantly different from that of the liquid phase, $\rho_2(MeCN) = 0.33$ (CL = 0.95). Furthermore, a comparison between the constant reaction values of the indole, $\rho_1(g) = 1.1$, and indolizine, $\rho_2(g) = 0.25$, series in the gas phase was carried out. These values, which are significantly different from each other ($0.99 < CL < 0.999$), show that the influence of the substituent groups on the ionization process in the gas phase is very different. Thus it could be hypothesized that the solvent greatly weakens the influence of the substituents on the reaction mechanism.

Finally it must be recalled that a statistical analysis cannot supply absolute answers, but only allows the experimental results to be compared and explained in terms of probability. Indeed, for this kind of analysis, an introduction of subjective data (confidence level, error distribution, etc.) is needed to explain the results in a positive or negative way.

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