

PYRIDINETHIONES—V

SPECTROSCOPIC INVESTIGATION AND ELECTRONIC STRUCTURE OF 3-FORMYL-2(1H)-PYRIDONES, -THIONES AND -SELONES

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Abstract—The 3-formyl-2(1H)-pyridone, -thione and -selone systems have been investigated by UV photoelectron, UV-visible, ¹H and ¹³C NMR spectroscopy. It is demonstrated that the electronic build-up of these systems as derived from the spectroscopic data may be correlated with their chemical behaviour through application of the perturbation model for chemical reactivity.

In a series of papers we have described the chemistry of 1-substituted 3-formyl-2(1H)-pyridones, -thiones and -selones.¹ The present contribution contains an investigation of the structures of these compounds by means of ultraviolet photoelectron, UV-visible, ¹H and ¹³C NMR and IR spectroscopy.

Helium I photoelectron spectra

As an approach to a correlation between (i) the chemical and spectroscopic properties and (ii) the electronic build-up of the 3-formyl-(2H)-2-pyridones (1), -2-pyridinthiones (2) and -2-pyridinselones (3) we have recorded the He(I) photoelectron (PE) spectra of 1–3b and c. The PE spectra of 1–3b (7–14 eV) are shown as Figs. 1–3. The measured ionization energies (IE's) below ca. 12 eV are given in Scheme 1 together with literature² data on *N*-methyl-(2H)-2-pyridone (4b) and *N*-methyl-(2H)-2-pyridinethione (5b) as well as measured IE's for *N*-methyl-

(2H)-2-pyridine selone (6b). The scheme presents our tentative assignment of the energy levels, divided into A'(σ) and A''(π) species according to the C_s symmetry of 1–6. A' species are further denoted by the atom of their expected highest density.

The spectra of 2 and 3 are qualitatively very similar, each showing three separate bands in the low-IE region. The intensities of these after correction for the variation in spectrometer resolution ($I = I_{\text{obs}}/E_{\text{kin}}^3$) have a ratio close to 2:1:2 indicating that the second band comprises one and the first and third band two ionization events each. This interpretation is supported by the structure of the first band of 2b and 3b which is resolved in a short vibrational progression ($\nu' = 1200 \pm 100 \text{ cm}^{-1}$) overlaying a single sharp peak. On removal of the formyl group, i.e.

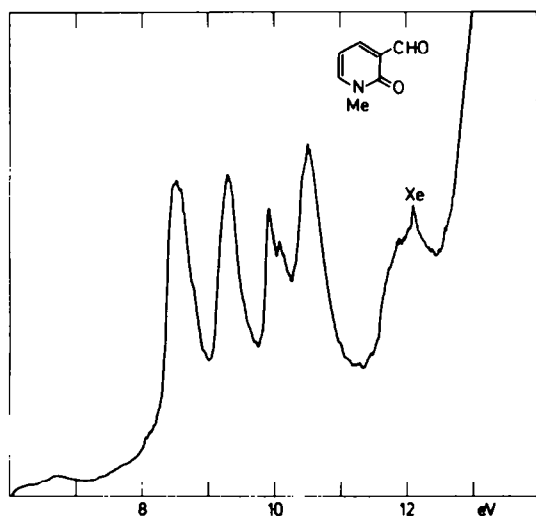


Fig. 1. Photoelectron spectrum of *N*-methyl-3-formyl-2(1H)-pyridone (1b).

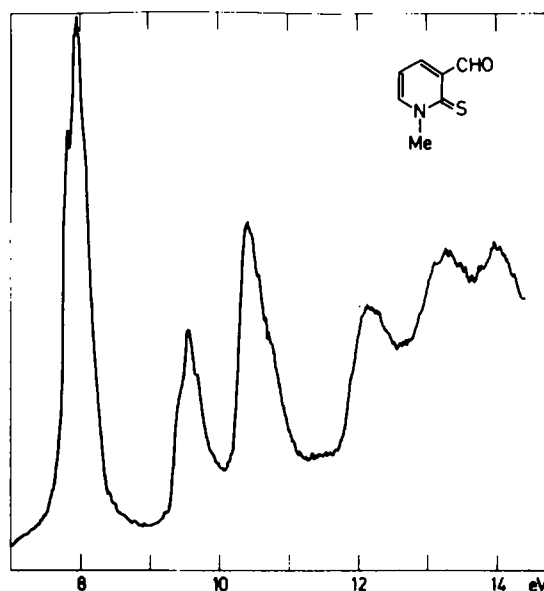
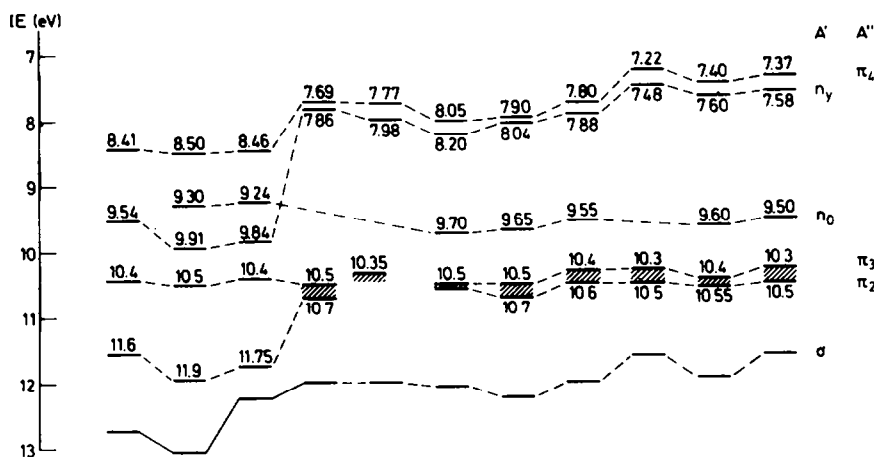


Fig. 2. Photoelectron spectrum of *N*-methyl-3-formyl-2(1H)-pyridinthione (2b).

Y	O			S					Se			
R ¹	H	CHO	CHO	H	H	CHO	CHO	CHO	H	CHO	CHO	
R ²	Me	Me	Pr'	Me	H	H	Me	Pr'	Me	Me	Pr'	
T (°C)	b	73	77	b	97	131	99	105	51	114	82	



Scheme 1. Ionization energies of substituted 2(1H)-pyridones, -thiones and -selones. (a) The levels marked σ denotes the onset of the region of overlapping bands. (b) Ref. 2.

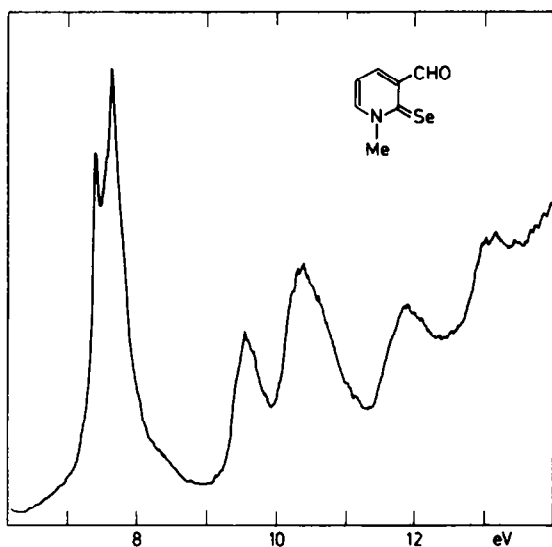


Fig. 3. Photoelectron spectrum of *N*-methyl-3-formyl-2(1H)-pyridinselone (3b).

going from 2 to 5 or from 3 to 6 the second band, at *ca.* 9.6 eV, disappears while the remaining bands are unaffected or show minor shifts to lower IE's. The second band can therefore be assigned to the A' lone pair of the formyl group in agreement with the reported⁴ value for benzaldehyde, 9.6 eV. On substitution of selenium for sulfur both components of the first band shift 0.3–0.4 eV to lower IE's while those of the third band are unaffected. The shifts of both components of the first band lie between those found for the hydrogen chalcogenides and the dimethyl chalcogenides (0.59 eV⁵ and 0.31 eV,⁶ respectively) and indicate that both ionizations take place from orbitals with high densities on the chalcogen atom. We therefore assign the low IE

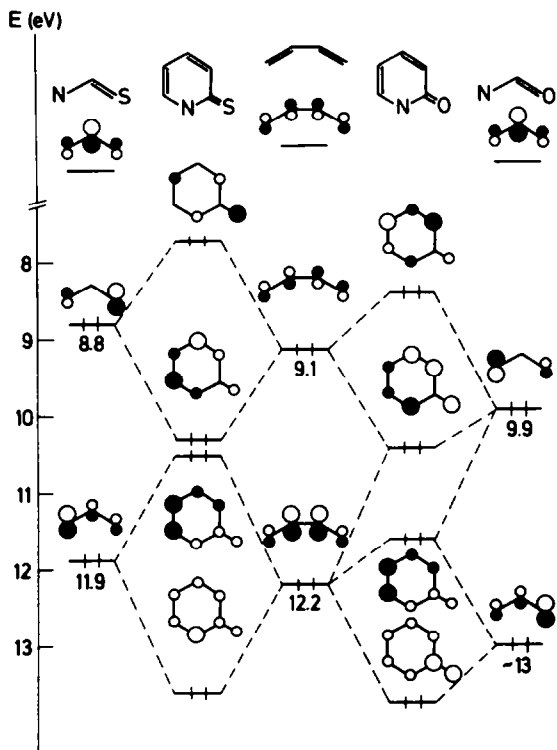
component of the first band which shows vibrational structure as π_4 and the other as the A' chalcogen lone pair. The assignment is supported by the fact that the vibrational structure is similar to that ($\nu' = 1300 \pm 100 \text{ cm}^{-1}$) seen in the lowest $\pi - \pi^*$ UV transition of 2b and 3b. The third band, at *ca.* 10.5 eV, is consequently assigned to ionizations from π_3 and π_2 which are accidentally nearly degenerate.

The spectra of the oxygen compounds, 1 and 4, differ in a characteristic way from those of their sulfur and selenium analogues. Compounds 1 show five and 4 four resolved bands in the low-IE region. Assuming that introduction of the formyl group as observed for 2, 3 and benzaldehyde³ gives rise to an additional A' level in the vicinity of 9.5 eV and raises the IE's of the A'' levels by 0.1–0.4 eV the ordering of the five levels of 1b–c becomes A'', A', A', A'', A'' as indicated in Scheme 1. The A' level at higher IE is, somewhat arbitrarily, correlated with the 9.54 eV level in 4 since these two levels give ionization bands with similar vibrational spacings (*ca.* 1300 cm^{-1}). However, in a delocalized description it makes little sense to discern between the two A' levels which both have the character of oxygen lone-pairs. It should be noted that the present set of data which includes the effects of sulfur–selenium interchange and formyl group shifts is in complete agreement with the assignment of the spectra of 4b and 5b given in Ref. 2.

It is often possible to get a reasonable estimate of the density distribution and nodal properties of the orbitals in a composite molecule by considering it as built up from simpler subunits.⁷ The π -electron system of 4–6 may be considered as composed of a butadiene and an amide, respectively thio- or selonoamide moiety in analogy with the discussion of the 5-membered heteroaromatics, furane, thiophene and pyrrole, in terms of butadiene-heteroatom interactions.⁸ This choice of subunits leaves the interacting atoms unchanged by the exchange of oxygen with sulfur. Thus the differences observed in the interaction pattern can be described

mainly in terms of the different energy gaps between the subunit levels.

Scheme 2 shows the interactions giving, to the right the 2-pyridone system of 4 and to the left the 2-pyridinethion system of 5. In view of the close similarity between the spectra of 5b and 6b the latter interaction



Scheme 2. Qualitative interaction diagram for 2(1H)-pyridone and -thione systems.

diagram is assumed to be representative of the selenium compounds also. The energies of the component levels are taken from the PE spectra of butadiene⁹ and *N*-methylformamide¹⁰ while those of the $\text{CH}_3\text{N}-\text{C}=\text{S}$ unit are an estimate based upon the reported¹¹ values for *N,N*-dimethylthioformamide (8.5 and 11.2 eV) and thioacetamide (8.97 and 12.65 eV). Only the larger interactions between close-lying levels are shown in the Scheme. However, polarization of the density distributions inside the subunits can be mimicked by the admixture according to the "orbital mixing rules" of Fukui¹² of small contributions from the more distant levels including the lowest unoccupied ones.¹³ The relative densities resulting from such extended but still qualitative treatment are shown in columns 2 and 4 of Scheme 2 and are in good agreement with CNDO/2 calculations on the model systems 1a and 2a.¹⁴ Scheme 2 suggests the following description of the π -levels of 4 and 5 listing the orbitals of the subunits, amide (A) and butadiene (B) after decreasing contributions:

Level	4	Compound	5
π_4	$\pi_2(B) - \pi_2(A)$		$\pi_2(A) - \pi_2(B)$
π_3	$\pi_2(A) + \pi_2(B) - \pi_1(B)$		$\pi_2(B) + \pi_2(A)$
π_2	$\pi_1(B) - \pi_1(A) + \pi_2(A)$		$\pi_1(A) - \pi_1(B)$
π_1	$\pi_1(A) + \pi_1(B)$		$\pi_1(B) + \pi_1(A)$

Tautomerism in 3-formyl-2H-2-pyridinethione (2a)

The PE spectrum of 3-formyl-(2H)-2-pyridinethione (2a) shown as Fig. 4 is more complicated than those of 1-3b. A total of six bands can be discerned below 12 eV, and, in particular, the wide variation in relative intensity among these bands suggests that more than one species is present. 2a may exist in tautomeric equilibrium with 2-mercaptopyridine-3-carbaldehyde (7a). While the amidic form predominates in polar solvents it has recently been firmly established¹⁵ that the equilibrium in the gas phase is displaced in favor of the pyridine tautomers of 2- and 4-hydroxy- and mercapto-pyridine. Katritzky *et al.*² interpreted the PE spectra of 2-pyridone and 2-pyridinethione in terms of an equilibrium mixture containing 25 and 10%, respectively, of the amidic forms. Variable temperature PE spectroscopy has recently been applied to the determination of enthalpy differences for these tautomerizations.¹⁶

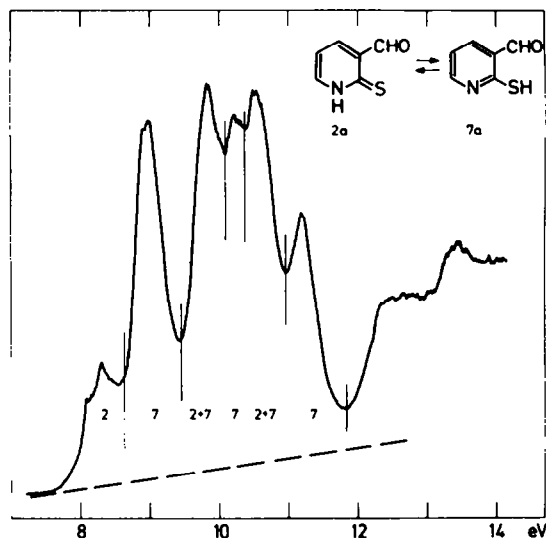


Fig. 4. Photoelectron spectrum of 3-formyl-2(1H)pyridinethione \rightleftharpoons 3-formylpyridin-2-thiol (7a).

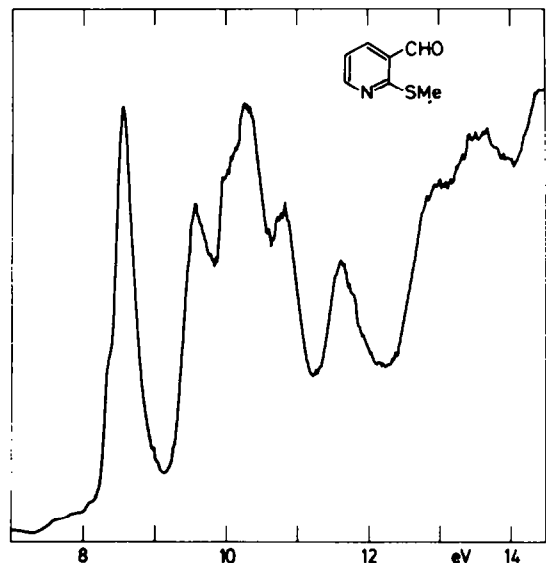
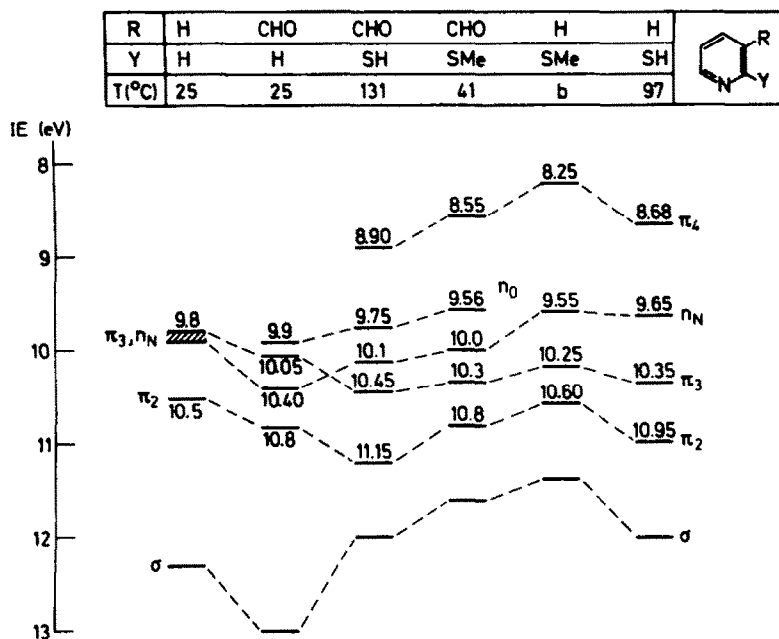


Fig. 5. Photoelectron spectrum of 2-methylthiopyridin-3-carbaldehyde



Scheme 3. Ionization energies of substituted pyridines. (a) The levels marked σ denotes the onset of the region of overlapping bands. (b) Ref. 2.

In order to determine whether the spectrum of **2a** can be interpreted in terms of the equilibrium $2a \rightleftharpoons 7a$ we have recorded the PE spectrum of 2-methylthiopyridine-3-carbaldehyde (**7b**) shown as Fig. 5 as a fixed reference for **7a**. The interpretation of this spectrum with the aid of the reference spectra of pyridine,¹⁷ pyridine-3-carbaldehyde and 2-methylthiopyridine² is illustrated in Scheme 3. The main principles inherent in this correlation scheme are:

(1) The formyl group as previously discussed will stabilize the three pyridine levels (π_2 , π_3 and n_N); therefore n_{CHO} is the only likely candidate for the 9.9 eV level in pyridine-3-carboxaldehyde.

(2) The inductive stabilization by the formyl group of the three pyridine levels is counteracted in the A' species by out-of-phase coupling with the lower-lying π_{CO} component but enhanced in the A' species by in-phase coupling to n_{CHO} .

(3) The PE spectra of thioanisole¹⁸ and 4-methylthiopyridine³ show negligible shifts of the A_2 π -orbital (+0.04 and -0.04 eV, respectively) relative to the corresponding orbitals of the parent compounds, benzene and pyridine. This implies that the inductive effect of the

methylthio group is negligible. Accordingly, this group perturbs the pyridine ring levels mainly by orbital interactions. Methylthio-substitution is therefore expected to stabilize the A' ring levels through in-phase coupling to the S_{3p} component but to destabilize the A' level through out-of-phase coupling to σ_{C-S} .

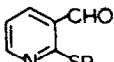
(4) The formyl-induced shifts of the three ring levels in pyridine and 2-methylthiopyridine should be of comparable magnitudes as should the methylthio-induced shifts of the levels in pyridine and pyridine-3-carbaldehyde.

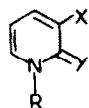
In the case of 2-methylthiopyridine our assignment is in agreement with the one given in Ref. 2. The band assignments of the tautomeric mixture of **2a** and **7a** are shown in Fig. 4. The correlation schemes, 1 and 3, show that the observed band maxima fit well into the general correlation. Thus the first band in Fig. 4 appears to originate in the π_4 and n_S levels of **2a** while the second arises from π_4 of **7a**. Assuming equal cross-sections of the three orbitals in question the intensity ratio of the two bands gives 16% of **2a** in the equilibrium mixture.

Inclusion of the spectrum of the 2-pyridinethione-2-pyridinethiol system in correlation Schemes 1 and 3 allows the assignment which was left undecided in Ref. 2 of the π_2 and π_3 -levels of the former component as coinciding with the π_3 -level of the latter, at 10.35 eV. The assignment finds support in the relative, energy corrected intensities of the five observed bands which are: 7.8–8.0 eV (1), 8.68 eV (6), 9.65 eV (6), 10.35 eV (7) and 10.95 eV (6). Our findings thus support the assumption given without proof in Ref. 16 that the second band originates solely from the pyridine tautomer.

UV-VIS spectra

The UV-VIS spectra of 1–3 were recorded in cyclohexane, absolute ethanol and concentrated hydrochloric acid. The spectra of **1b**, **2b** and **3b** are shown as Fig. 6–8, respectively. Absorption maxima and extinction coefficients are listed in Table 1.

	X	Y	R
1	CHO	O	a H
2	CHO	S	b CH ₃
3	CHO	Se	c CH(CH ₃) ₂
4	H	O	d CH(CH ₃)C ₆ H ₅
5	H	S	e C ₆ H ₅
6	H	Se	
7			a H b CH ₃



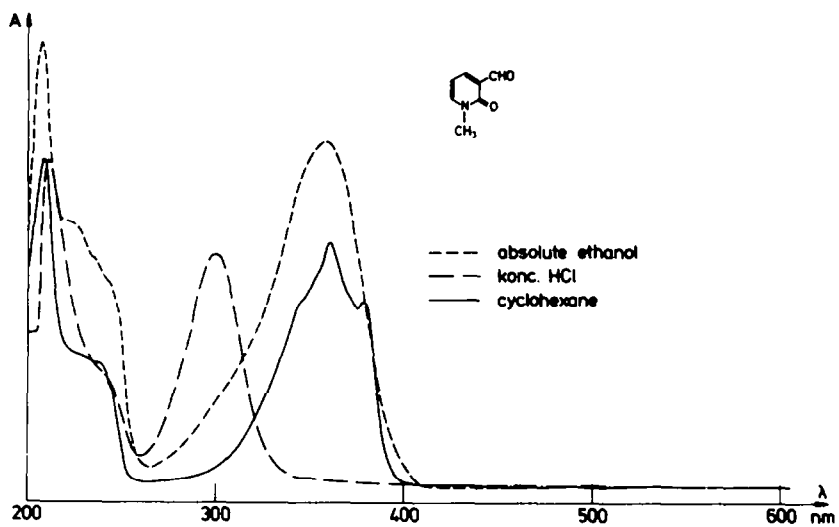


Fig. 6. UV-VIS spectrum of 1b.

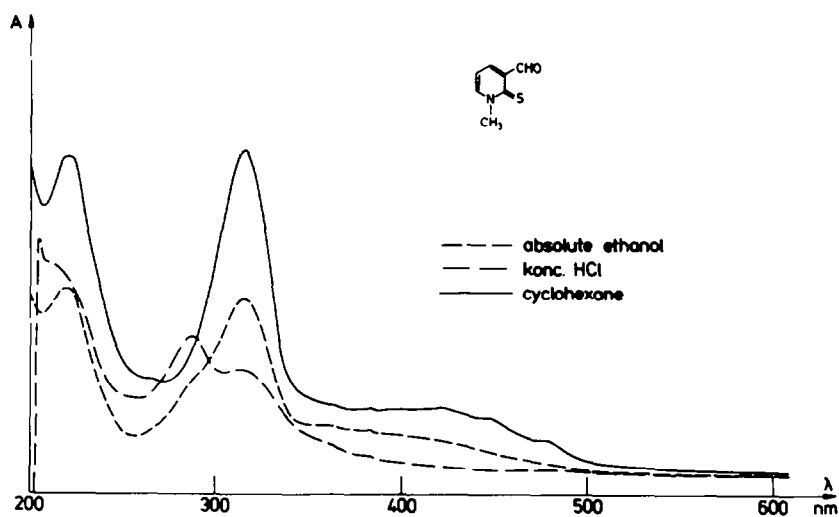


Fig. 7. UV-VIS spectrum of 2b.

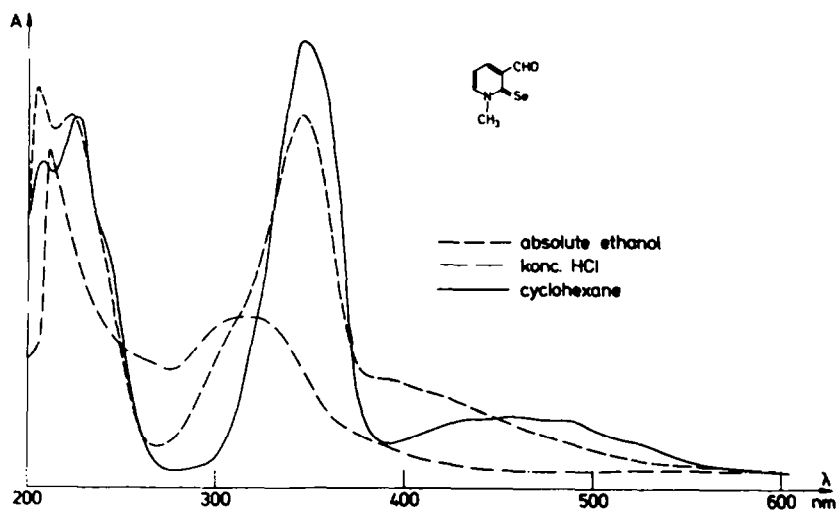


Fig. 8. UV-VIS spectrum of 3b.

The spectra of 1-3 recorded in concentrated hydrochloric acid are very similar to each other and closely resemble the previously reported spectra of pyridinium salts.¹⁹ Thus, compounds 1-3 are all protonated on the chalcogen atom to give substituted pyridinium ions.

In the spectra recorded in cyclohexane the extinction coefficient of the longest-wavelength maximum varies from 10^4 for 1 to $2 \cdot 10^3$ for 3 indicating that the band is caused by a $\pi - \pi^*$ transition. This absorption band displays a series of submaxima (three in the case of 1 and four for 2 and 3) corresponding to a vibrational progression with a spacing of *ca* 1200 cm^{-1} . The occurrence of comparable vibrational progressions in the lowest-energy $\pi - \pi^*$ transition and in the lowest energy ionization band supports the interpretation that the latter band originates from ionization of the highest occupied π -level.

In addition to the above mentioned band compounds 1-3 should display a long-wavelength $n - \pi^*$ transition band but no such band has been discerned in the spectra. Presumably it is hidden under the more intense $\pi - \pi^*$ band. This assumption is in accord with the photoelectron spectra which show that the highest occupied A'

level (chalcogen lone pair) partly overlaps the π_4 level (2 and 3) or falls below this level (1).

It has been argued²⁰ that the decreases in excitation energies observed through series of simple amide, thioamide and selonoamide structures are caused by a simultaneous raise of the highest occupied—and lowering of the lowest unoccupied π -level. This conclusion may find some support in photoelectron data: The decrease in excitation energy is 0.5 eV going from thio-selenourea,²⁰ at the same time the l. ionization band (corresponding to coinciding π - and $n_{\text{chalcogen}}$ -levels) is raised by only 0.25 eV (from 8.41¹¹ to 8.15²¹ eV).

In the series 1-3 the red-shift of the $\pi - \pi^*$ band measured on the first vibrational peak in the cyclohexane spectra is *ca* 100 nm going from oxygen to sulfur and further *ca* 40 nm going from sulfur to selenium. These values correspond to decreases in excitation energy of 0.7 and 0.2 eV, respectively. In comparison the photoelectron spectra of 1-3 show that the π_4 -level is raised by 0.6 and 0.5 eV, respectively. These data indicate that the lowest unoccupied π^* -level may not necessarily be stabilized through the series O-S-Se when the amide structure is incorporated in a conjugated system.

Table 1. UV-VIS λ_{max} (log ϵ) of *N*-substituted-3-formyl-2(1H)-pyridones, -thiones and -selones

Compound						
1 b	300(3.88)		236sh(3.61)		211(4.03)	
1 c	302(3.90)		236sh(3.56)		212(4.05)	
1 d	302(3.50)		238sh(3.30)		211(3.84)	
1 e	305(3.88)		228sh(3.95)		211(4.07)	
2 a	313(3.66)		283(3.85)		211(3.97)	
2 b	315(3.71)		286(3.93)		212(4.11)	
2 c	315(3.68)		273(3.88)		211(4.14)	
2 d	315(3.72)		290(2.89)		213(4.23)	
2 e	321(3.72)		289(3.89)		-	
3 b	320(3.74)		257sh(3.60)		211(4.04)	
3 c	328(3.74)		260sh(3.61)		212(4.08)	
3 d	290sh(3.85)		-		213(4.35)	
3 e	335(3.65)		250sh(3.88)		213(4.22)	
7 b	322sh(3.73)		297(4.05)		213(3.98)	
abs. ethanol						
1 b	358(3.82)	242sh(3.60)	234sh(3.64)	221sh(3.71)	-	208(3.93)
1 c	360(3.86)	243sh(3.60)	236sh(3.63)	225sh(3.69)	-	207(4.05)
1 d	360(3.90)	-	237sh(3.76)	-	-	206(4.33)
1 e	360(3.82)	-	238sh(4.01)	-	-	206(4.16)
2 a	375(3.32)	320(4.02)	293sh(3.75)	-	216(4.02)	207sh(3.99)
2 b	375(3.39)	314(4.09)	290sh(3.79)	-	218(4.14)	-
2 c	404(3.38)	319(4.06)	292sh(3.64)	-	220(4.04)	205(4.00)
2 d	388(3.49)	318(4.06)	294sh(3.77)	-	226sh(4.26)	208(4.42)
2 e	385(3.49)	321(3.99)	298sh(3.78)	240sh(3.92)	218sh(4.10)	203(4.19)
3 b	390sh(3.45)	345(4.02)	309sh(3.64)	-	222(4.02)	210(4.05)
3 c	400sh(3.42)	350(4.01)	313sh(3.61)	-	220(4.00)	205(4.07)
3 d	407sh(3.47)	352(4.02)	316sh(3.65)	-	221sh(4.21)	211(4.25)
3 e	413sh(3.50)	357(3.96)	322sh(3.72)	243(3.94)	219sh(4.14)	211(4.18)
7 b	338(3.44)	275(3.91)	253(3.73)	-	224(4.16)	208sh(3.95)

Table 1.(Contd)

Cyclohexane								
1 b	-	379(3.77)	361(3.89)	346sh(3.77)	244sh(3.51)	237sh(3.60)	277(3.63)	209(4.02)
1 c	-	383(3.80)	364(3.92)	346sh(3.79)	245sh(3.56)	241(3.61)	228(3.62)	210(4.07)
1 d	-	383(3.86)	365(3.98)	349sh(3.85)	-	238(3.98)	-	214(4.06)
1 e	-	385sh(3.84)	369(3.96)	358sh(3.91)	-	239(3.71)	218sh(4.03)	207(4.27)
2 a	-	-	-	420(3.38)	320(4.22)	230sh(3.86)	217(4.08)	200(4.27)
2 b	-	479(3.10)	449(3.38)	425(3.39)	316(4.18)	-	223(4.11)	203(3.99)
2 c	-	477sh(3.15)	449(3.41)	428(3.43)	318(4.21)	-	223(4.13)	201(4.15)
2 d	-	479(3.25)	450(3.50)	438(3.52)	321(4.22)	-	238sh(4.03)	215(4.35)
2 e	-	499(3.10)	468(3.41)	441(3.45)	322(4.13)	-	242sh(3.91)	208(4.24)
3 b	520sh(2.99)	484(3.24)	457(3.26)	429(3.23)	350(4.14)	237sh(3.90)	225(4.06)	206(4.00)
3 c	521sh(3.08)	482(3.24)	462(3.27)	441(3.24)	353(4.10)	238sh(3.82)	225(3.99)	207(4.02)
3 d	520sh(3.13)	483(3.35)	458(3.37)	438(3.35)	355(4.18)	243sh(3.97)	228sh(4.30)	207(4.35)
3 e	548sh(3.10)	515(3.24)	483(3.29)	458(3.26)	362(4.12)	290sh(3.33)	245sh(3.93)	208(4.26)
7 b				343(3.48)	283sh(3.73)	274(3.99)	223(4.19)	

The solvent-induced shift of the long-wavelength band reveals a striking difference between on one hand 1 and on the other 2 and 3. The spectra of 1 display a blue-shift of ca 20 nm going from cyclohexane to ethanol while the corresponding shift in the spectra of 2 and 3 is ca 75 nm. This difference in behaviour may be taken in support of the difference in electronic structure which was deduced from the photoelectron data and shown in Scheme 2: It may reasonably be assumed that ethanol mainly solvates 1–3 through hydrogen-bonding to the negatively charged chalcogen atom and thereby reduces the negative charge on this atom. In consequence the π_4 -level of 2 and 3, which is mainly localized on this atom, is stabilized relative to the lowest π^* -level which is mainly localized in the ring. On the other hand, both of these levels are mainly located in the ring of 1; hydrogen bonding to the chalcogen atom will consequently have a much smaller influence on their energy separation.

¹H NMR spectra

Chemical shifts and coupling constants for compounds 1–3, a–d are given in Table 2. The coupling constants $J_{4,5}$ and $J_{5,6}$ are identical inside the experimental error and 3–5 times $J_{4,6}$. This gives rise to a simple pattern of a doublet of doublets, a triplet and a doublet of doublets for H(4), H(5) and H(6), respectively.

Comparison of the chemical shift of the three ring-protons to the values found^{22,23} for 3-unsubstituted pyridones and -thiones shows that the order, $\delta(5) < \delta(4) < \delta(6)$ is unchanged by the introduction of the electron-withdrawing formyl group. This group deshields all three protons but in an alternating manner, i.e. the shift in 1 as well as 2 is 0.4–0.5 ppm for the 4- and 6-positions but only 0.1–0.2 ppm for the 5-position.

Replacement of oxygen and sulfur, i.e. going from 1 to 2, results in a systematic shielding of H(4) and deshielding of H(5) and H(6) and these trends continue going from 2 to 3. The variations can hardly be ascribed to variation in the diamagnetic anisotropy of the C=Y (Y = O, S, Se) bond alone since H(4) and H(6) are situated roughly symmetrically with respect to the axis of this bond. On the other hand, the chemical shift changes do follow those of the corresponding carbon atoms (see later). The major contribution to the observed chemical shift changes could therefore be variations in charge density transmitted through the carbon skeleton.

Stewart and Siddall²² in a study of *N*-alkyl-2-pyridones found that substitution of sulfur for oxygen caused a chemical shift change which was +0.32, 0.47 and 0.79 ppm for the α -protons of *N*-CH₃, *N*-CH₂CH₃ and *N*-CH(CH₃)₂, respectively. The increase with the bulk of the substituent of these values was ascribed to steric repulsion between the chalcogen atom and the β -carbon atom(s) which forces the α -hydrogen atom(s) into close proximity to the carbonyl double bond. The same effect is operative in the series 1–3. Thus, $\delta(N\text{-CH}_3)$, $\delta(N\text{-CH}(\text{CH}_3)_2)$ and $\delta(N\text{-CH}(\text{CH}_3)\text{Ph})$ are changed by +0.46, +1.11 and +1.24 ppm, respectively, going from oxygen to sulfur. The corresponding changes from sulfur to selenium are +0.04, +0.19 and +0.27 ppm. Investigations of *N,N*-dialkylamides, -thioamides and -selenoamides indicate that the diamagnetic deshielding increases in the order C=O \ll C=S < C=Se.²⁴ The observed chemical shift changes can thus be explained alone in terms of this deshielding acting on the same fixed conformation of the *N*-isopropyl and - α -phenethyl groups in 1–3. The present data are,

however, insufficient to discern this situation from one where the ordering of the *N*-substituent increases through the series O \rightarrow S \rightarrow Se. In either case the results indicate that orientation of a β -carbon atom toward the C=S or C=Se group gives rise to a strongly repulsive steric interaction. This conclusion supports our previous suggestion^{1b} that steric repulsion is the factor impeding the cyclization step in the formation of *N*-*t*-butyl-3-formyl-2(1H)-pyridinethione and -selone.

¹³C NMR spectra

Analysis of the ¹³C NMR spectra of 1–3 showed that the *N*-substituent has little influence (± 2 ppm) on the chemical shifts of the ring and formyl carbon atoms. The mean values observed for compounds b–e in each of the three series are given in Table 3 together with lit²⁶ data on *N*-methyl-2-pyridone (4b) and -thione (5b). The signal from C(2) is found at 162 ppm for 1 and 4 and at 180–182 ppm for 2, 3 and 5. The deshielding of C(2) by ca 20 ppm on substitution of oxygen with sulfur is in agreement with previous studies reporting shifts of 15–34 ppm for simple and heterocyclic amide structures.^{26–28} The insensitivity of the C(2) chemical shift to replacement of sulfur with selenium is likewise preceded in simple amides where deshieldings of 2–5 ppm have been reported.²⁸

For the ring atoms, C(3)–C(6), it is noted that C(6) becomes slightly less and C(4) slightly more shielded through the series O \rightarrow S \rightarrow Se while a more pronounced deshielding of C(5) is observed. The introduction of the 3-formyl group has virtually no influence in these three positions. The chemical shift of C(3) shows a particular feature. The low-field value of 119 ppm in 4b increases to 139 ppm in 1, i.e. on introduction of the 3-formyl group, and to 134 ppm in 5b, i.e. on exchange of oxygen with sulfur. Although we cannot at present give any rationalization of this fact it is evident from the values observed for 2 (138 ppm) that the two deshielding effects are not additive. Since the ligands of C(4)–C(6) are identical for all of the compounds in Table 3 the chemical shift changes experienced by these three atoms may reasonably be taken to reflect changes in effective nuclear charge.

IR-spectra

The IR-spectra of compounds 1c, 2c and 3c are shown as Fig. 9–11, respectively. The assignment of a band due to the N–C=Y moiety is straightforward for 1 where a "normal" amide band is found at 1655 cm⁻¹. However, the group frequencies of thio- and selenoamide structures fall into the "fingerprint" region below 1300 cm⁻¹ where coupling to several other bond vibrations is unavoidable in low-symmetry molecules.^{29–31} Consequently, no single characteristic absorption bands can be assigned to the thio- or selenoamide moieties of 2 and 3. Instead, as is evident from Fig. 9–11, several bands below 1300 cm⁻¹ show small (<30 cm⁻¹) shifts from 2 to 3. In conclusion, the IR spectra of 2 and 3 furnish little formation of immediate analytical or structural interest.

DISCUSSION

In the perturbation approach to chemical reactivity³² nucleophilic reactivity is described in terms of three parameters (i) the energy of the highest occupied molecular orbital (HOMO), (ii) the coefficient of this orbital at the reactive site and (iii) the negative charge density at this site. The corresponding parameters for electrophilic

Table 2. ¹H NMR chemical shifts^a of *N*-substituted-3-formyl-2(1H)-pyridones, -thiones and -selones

Compounds	H(4) dd	H(5) t	H(6) dd	CHO	J _{4,5}	J _{5,6}	J _{4,6}	other protons
1 a	8.07m	6.57	8.07m	10.3	7	7	2	11.32 (broad, s, NH) ^b
1 b	8.02	6.40	8.23	10.12	6.4	6.4	2.2	3.50 (s, CH ₃)
1 c	7.97	6.50	8.20	10.17	6.2	6.2	2.0	5.17 (qi, 6, CH) 1.40 (d, 6, CH ₃)
1 d	7.91	6.44	8.07	10.11	6.5	6.5	2.0	7.33 (s, C ₆ H ₅) 6.22 (q, 7, CH) 1.75 (d, 7, CH ₃)
1 e	8.08	6.57	8.19	10.15	7.0	7.0	2.3	7.05 (s, C ₆ H ₅)
2 a	7.85	6.89	7.96	10.64	6.1	6.1	1.5	7.90 (broad, s, NH)
2 b	7.81	6.93	8.54	10.72	8.7	8.7	1.8	3.96 (s, CH ₃)
2 c	7.80	7.02	8.58	10.65	7.5	7.5	1.5	6.28 (h, 6.8, CH) , 1.45 (d, 6.8, CH ₃)
2 d	7.78	6.91	8.30	10.65	6.2	6.2	1.5	7.40 (s, C ₆ H ₅) 7.46 (q, CH) 1.81 (d, 6.8, CH ₃)
2 e	7.90	6.98	8.35	10.56	6.8	6.8	1.5	7.55 (s, C ₆ H ₅)
3 b	7.65	7.10	8.55	10.50	7.0	7.0	2.0	4.00 (s, CH ₃)
3 c	7.62	7.12	8.60	10.50	7.0	7.0	2.0	6.47 (qi, 6, CH) 1.45 (d, 6, CH ₃)
3 d	7.73	7.10	8.40	10.55	6.1	6.1	2.0	7.73 (m, CH) 7.45 (s, C ₆ H ₅) 1.81 (d, 7, CH ₃)
3 e	7.85	7.20	8.50	10.61	7.0	7.0	1.5	7.53 (s, C ₆ H ₅)

^aDMSO-*d*₆; values in ppm relative to TMS; s (singlet), d (doublet), t (triplet), q (quartet), qi (quintet), h (heptet), m (multiplet).

^bIn *t*-butyl alcohol.²⁵

Table 3. ^{13}C NMR chemical shifts (ppm from TMS) of *N*-substituted-3-formyl-2(1H)-pyridones, thiones and -selones

Compound	C(2)	C(3)	C(4)	C(5)	C(6)	CHO
1 ^a	162	139	140	105	141	190
2 ^a	182	138	136	112	144	192
3 ^a	182	140	135	114	145	193
4b ^b	162	119	140	105	140	
5b ^b	180	134	136	113	141	

^aIn $\text{DMSO-}d_6$; average values (no deviation exceeding ± 2 ppm) for compounds b-e.

^bIn CDCl_3 ; Ref. 26.

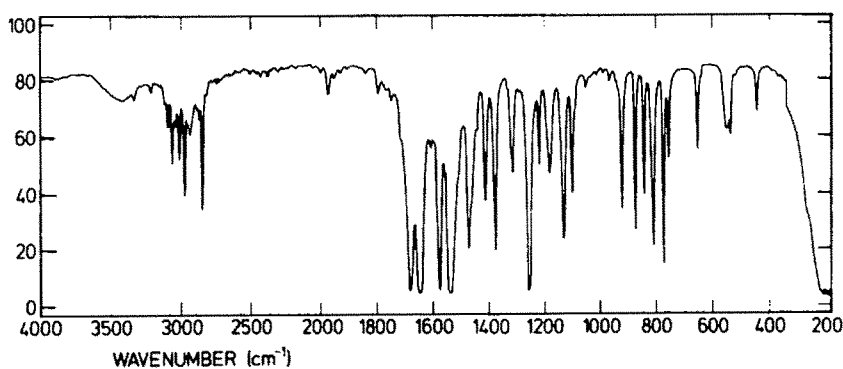


Fig. 9. IR spectrum (KBr) of 1c.

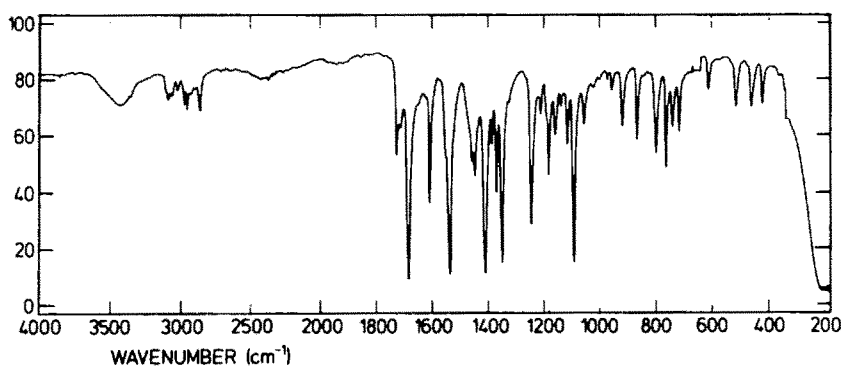


Fig. 10. IR spectrum (KBr) of 2c.

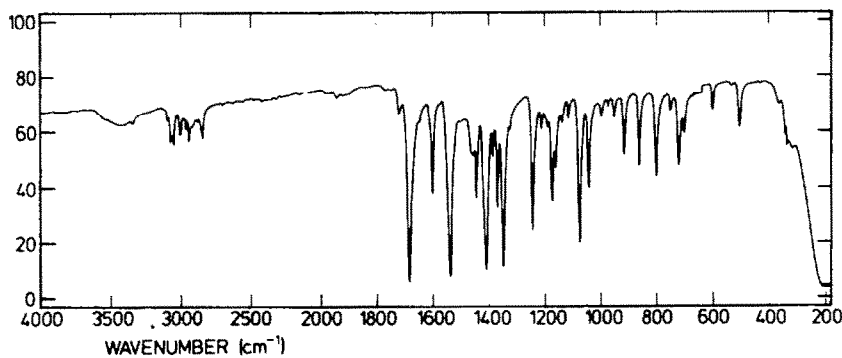


Fig. 11. IR spectrum (KBr) of 3c.

reactivity are (i) the energy of the lowest unoccupied molecular orbital (LUMO) (ii) the coefficient of this orbital at the reactive site and (iii) the positive charge density at this site. Bond formation between a nucleophile and an electrophile is favoured by a small energy gap between the HOMO of the former and the LUMO of the latter and high coefficients of these orbitals at the reaction sites or by high charge densities at these sites. In the first case, the "soft" or "frontier orbital controlled" reaction, the activation barriers is lowered mainly by the stabilizing HOMO-LUMO interaction and in the second, the "hard" or "charge controlled" reaction, mainly by coulombic stabilization between opposite charges. An estimate of the variation of the basis parameters can be obtained from PE-, UV-VIS-, and NMR-spectra. Therefore the model is well suited for predicting variations in relative reactivities, hard-soft behaviour and ambident properties through a series of related molecules.

The present analysis of the PE-spectra of 1-6 supported by the element- and solvent-induced shifts in the UV-VIS spectra indicates that substitution of sulfur or selenium for oxygen affects the energy as well as the distribution of the HOMO. The destabilization caused by this substitution exceeds the stabilization of the HOMO on introduction of the formyl group so that the HOMO-energy of 2 and 3 is higher than that of both 1 and 4. Furthermore, the HOMO of the oxygen compounds is mainly located at the diene moiety of the ring while that of the sulfur and selenium compounds is concentrated on the chalcogen atom. At the same time the ^{13}C NMR spectra suggest that the substitution reduces the polarization of the ring and, thereby, the negative charge at the 5-position of 1, respectively the 3- and 5-positions of 4.

These variations lead to the following predictions regarding the nucleophilic reactivity of 1-6: The reactivity should increase in the order $1 < 4 < 2 < 5 < 3 < 6$. The reactive site should change from the diene moiety of the ring in 1 and 4 to the chalcogen atom of 2, 3, 5 and 6. Thus, a sulfur or selenium atom although it increases the net nucleophilicity of the molecule also protects the ring carbon atoms against attack by soft as well as hard electrophiles by depleting the reactive ring positions of HOMO density as well as of negative charge.

Literature data on compounds 4 and 5 as well as our own experience with 1-3 are in good agreement with these predictions. Thus, 4 are more reactive than pyridine toward electrophilic reagents, e.g. bromine and nitrating acid, with the 3- and 5-positions as the reactive sites.³³ In contrast no substitution product has been observed on treatment of either 5³⁴ or 2³⁵ with bromine and while 5 are 3,5-dideuterated with $\text{D}_2\text{SO}_4\text{-D}_2\text{O}$ and hydroxymethylated with $\text{CH}_2\text{O-HCl}$ it is stated that these reactions require more drastic conditions than the corresponding reactions of 4.^{23,24} On the other hand 5 are readily S-alkylated by alkylbromides and -iodides while these mild electrophiles leave 4 untouched.³⁶

The diene reactivity of 4 leading to Diels-Alder addition at the 3,6-position is well documented, see e.g. Refs. 37 and 38. A similar adduct has been reported for 5b but the N-unsubstituted compounds for which a choice of reaction paths exist show differences from oxygen to sulfur. 3- and 6-methylated 4a with N-phenylmaleic imide give the Diels-Alder adduct as the main product³⁹ while 5a gives exclusively the product of a Michael addition with sulfur as the nucleophilic site.⁴⁰

Finally, we were unable to observe Diels-Alder adducts on treatment of 2 with dienophiles such as dimethyl acetylenedicarboxylate and N-phenylmaleic imide.

EXPERIMENTAL

The preparation of the compounds used in this study is described in our previous papers.¹ The following instrumentation was used. IR: Perkin-Elmer model 457 (KBr), UV-visible: Beckman ACTA III (cyclohexane, abs. ethanol and conc. HCl), ^1H NMR: Jeol C-60 HL (DMSO-d_6), ^{13}C NMR: Jeol FX-60 (DMSO-d_6), UPS: Perkin-Elmer PS 18 equipped with He(I) source and heated target chamber; vaporization temperatures are given in Schemes 1 and 3. The spectra were calibrated by means of the Ar and Xe $2\text{P}_{3/2}$ peaks; the reproducibility varied between ± 20 and ± 50 mV and the experimental resolution between 30 and 60 mV. In both cases the poorest values were found for the least volatile compounds.

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