Journal of Organometallic Chemistry
Elsevier Sequoia S.A., Lausanne
Printed in The Netherlands

MEASUREMENTS OF pK_a AND HYDROGEN-BOND STRENGTHS OF SOME ORGANOSILICON- AND ORGANOGERMANIUM-SUBSTITUTED PYRIDINE *N*-OXIDES

MICHAEL A. WEINER AND PAUL SCHWARTZ
Department of Chemistry, The City College of the City University of New York, New York, New York 10031 (U.S.A.)

(Received August 7th, 1971)

SUMMARY

The results of pK_a measurements on 4-substituted pyridine *N*-oxides show that organosilicon and organogermanium substituents are responsible for a decreased basicity relative to the tert-butyl derivative and the unsubstituted compound. No such effect is shown in the 3-substituted compounds. The results of hydrogen-bonding studies on the 4-substituted pyridine *N*-oxides (using methanol and phenol as acids) show that the organometallic substituents are responsible for a decreased basicity relative to the tert-butyl derivative, but not when compared to the unsubstituted compound. The effect of changing experimental conditions on the nature of the pyridine *N*-oxide moiety is discussed.

INTRODUCTION

The inductive electron-withdrawing behavior of the N–O group in pyridine *N*-oxide is opposed by back-donation from the oxygen 2 p_π-orbital into the π-system of the ring, thus increasing the π-electron density at the 4-position. This phenomenon is well documented[1].

Previous data from this laboratory[2] on the N–O stretching frequencies of some pyridine *N*-oxides, substituted in the 4-position with organosilicon and organogermanium substituents, have shown a substantial increase in ν(N–O) for the organometallic derivatives when compared to the tert-butyl derivative and significantly, even when compared to the unsubstituted pyridine *N*-oxide. The N–O stretching frequency is known to be related to the nature of the 4-substituent[3]. Apparently the greater the electron-withdrawal by the substituent, the greater the extent of O→ring π-backbonding, and the greater the N–O bond order and N–O stretching frequency. Thus evidence was apparently presented in favor of the electron-withdrawing behavior of the organometallic substituents. Such behavior, we believed, was prompted by the increased π-electron density at the 4-position, and this implied to us the presence of dative p_π–d_π bonding involving the silicon or germanium.

The present report concerns the results of pK_a measurements on pyridine *N*-oxides containing organosilicon and organogermanium substituents, as well as measurements of hydrogen-bond strengths using methanol and phenol as hydrogen-bonding acids. The results presented here substantiate in part the conclusions of the previous report, but also point out the sensitivity of the electron-withdrawing effect of these organometallic groups to changes in the nature of the "donor" organic moiety.

RESULTS AND DISCUSSION

The pK_a data in Table 1 were obtained by the spectrophotometric method[4] on aqueous solutions of the 4-substituted pyridine *N*-oxides, using the 256 nm peak in the ultraviolet spectra of these compounds. The value of 0.82 for the unsubstituted pyridine *N*-oxide compares favorably with the value of 0.79 obtained by Jaffe and Doak[4]. The results here show a substantially greater basicity for the 4-tert-butyl derivative compared to the 4-substituted organometallic derivatives, with no variation among the results obtained for the various organometallic derivatives. Moreover the basicities of the organometallic derivatives are even somewhat less than that of the unsubstituted compound. Thus the organometallic groups cause a net stabilization of the neutral basic species over the *N*-hydroxypyridinium acidic species. If we make the reasonable assumption that in the acid form the organometallic groups have a minimal electron-withdrawing effect (*vide infra*), or even a donor effect, then the net stabilization of the basic form must be due to the predominance of an electron-withdrawing effect in the basic form, in which the π-electron density at the 4-position is enhanced. In the 3-substituted compounds there is no difference between the results obtained for the tert-butyl compound and the results obtained for the organometallic compounds (or the unsubstituted compound) indicating the insensitivity of the 3-position to the O→ring back-bonding effect.

Recently Zuckerman *et al.*[5] have criticized the interpretation of pK results in terms of substituent bonding effects. Thus in the case of substituted benzoic acids in aqueous media, although the pK_a results were supposed to show the electron-withdrawing nature of the trimethylsilyl group, this was not supported by the enthalpy values for the substituted benzoic acids, obtained by measuring K_a at various temperatures. In light of this, it seemed desirable to obtain some basicity measurements on the pyridine *N*-oxides which could be more directly related to the strength of an acid–base interaction. Recent studies have shown a linear relationship between

TABLE 1

pK_a DATA ON SUBSTITUTED PYRIDINE *N*-OXIDES[a]

Substituent	pK_a	
	4-Position	3-Position
H	0.82	0.82
$(CH_3)_3C$	1.16	0.84
$(CH_3)_3Si$	0.60	0.85
$(CH_3)_3Ge$	0.60	0.86
$(C_2H_5)_3Si$	0.63	

[a] Measured in aqueous media. Values obtained at 24–28°.

ΔH of base–alcohol hydrogen-bonding interactions and the shifts in the O–H stretching frequencies of these alcohols in the presence of the hydrogen-bonding bases[6]. Measurements of frequency shifts for phenols[7,8] and methanol[9] in the presence of various pyridine *N*-oxides have previously been determined, and a relationship with base-strength has been assumed[8].

In the present study, methanol (in CCl_4) was used as the hydrogen-bonding acid. Although methanol is a fairly weak acid for hydrogen-bonding studies, the hydrogen-bonded O–H stretching frequencies observed were in the region of 3300–3400 cm^{-1}, a region uncluttered by various C–H absorptions. Thus with the use of a 6 mm pathlength cell, allowing for the use of 0.04 *M* methanol solutions, peaks due to both free and hydrogen-bonded O–H stretching vibrations were fairly sharp and the data in Table 2 could be measured to better than ± 5 cm^{-1}. The results (Table 2) show a greater base-strength for the 4-tert-butyl derivative than for the compounds with an organometallic group in the 4-position, indicating once again the greater net electron-withdrawing effect of the organometallic group. However the 4-substituted organometallic derivatives seem to show only a slightly greater electron-withdrawing effect, if any, compared to the unsubstituted compound. In the 3-substituted compounds there is, as before, no difference between the results obtained for the tert-butyl and organometallic derivatives.

TABLE 2

$\Delta\nu$(O–H) VALUES FOR METHANOL ADDUCTS WITH SUBSTITUTED PYRIDINE *N*-OXIDES[a]

Substituent	$\Delta\nu$(O–H) (cm^{-1})	
	4-Position	3-Position
H	280	280
$(CH_3)_3C$	310	290
$(CH_3)_3Si$	270	285
$(CH_3)_3Ge$	280	285
$(C_2H_5)_3Si$	275	

[a] Measured in CCl_4 solution. The ν(O–H) for unassociated methanol in CCl_4 is 3640 cm^{-1}.

In order to further compare the 4-substituted organometallic derivatives with the unsubstituted compound, phenol was used as the hydrogen-bonding acid in a subsequent study. However, a study of $\Delta\nu$(O–H) did not appear feasible with phenol on account of the broadness of the band due to the hydrogen-bonded ν(O–H) and interference from C–H absorptions[7]. Work by several groups[10,11] however has established a linear relationship between the phenol hydroxy proton chemical shift in the presence of hydrogen-bonding bases, and the enthalpy of the acid–base interaction [or $\Delta\nu$(O–H)]. Under conditions of complete complexation of the phenol, an increased donor strength of the base leads to a greater downfield chemical shift (measured here from tetramethylsilane). The proton absorptions are fairly sharp singlets and thus the data in Table 3 are measurable to within ± 0.02 ppm. Such preciseness is very desirable for this study and is not often obtained in measurements of $\Delta\nu$(O–H). Possible donor anisotropy effects were not taken into account because of the closely related nature of the donors[10]. Although there has been no previous study of this type using pyridine *N*-oxides as bases, the results on some typical pyridine *N*-oxides obtained in this study correlate well with the $\Delta\nu$(O–H) data obtained by Herlocker, Drago, and Meek[7] (see Table 3). Solubility problems prevented work on some other pyridine *N*-oxides.

From the data given in Table 3, it appears that the 4-tert-butyl derivative shows, as before, a significantly greater base-strength than the 4-substituted organometallic derivatives, indicating the greater electron-withdrawing behavior of the organometallic groups. This effect does not appear in the 3-substituted compounds. However the 4-substituted organometallic derivatives show no greater electron-withdrawing effect than the unsubstituted compound, and here even have a slight donating effect.

TABLE 3

CHEMICAL SHIFTS AND $\Delta\nu$(O–H)[a] VALUES FOR PHENOL ADDUCTS WITH SUBSTITUTED PYRIDINE *N*-OXIDES

Substituent	δ^b (ppm) [$\Delta\nu$ (cm^{-1})]	
	4-Position	3-Position
H	10.10 (468)	10.10 (468)
$(CH_3)_3C$	10.51	10.26
$(CH_3)_3Si$	10.15	10.25
$(CH_3)_3Ge$	10.20	10.21
CH_3O	11.02 (>530)	
CH_3	10.54 (512)	
$CO(CH_3)$	8.96 (400)	

[a] From ref. 7. [b] Measured in CH_2Cl_2 solution. Values are downfield from TMS.

Thus the results of the hydrogen-bonding studies, using both methanol and phenol, apparently show a diminished electron-withdrawing effect for the organometallic groups in the hydrogen-bonded form of the pyridine *N*-oxide species (with an even more diminished effect in the presence of the stronger acid, phenol). It is reasonable to assume that in the hydrogen-bonded form, there is a decrease in the magnitude of O→ring back-donation, with a resultant decrease in the amount of π-electron density at the 4-position of the ring. The decreased electron-donating behavior of the 4-position prompts a diminished electron-withdrawing effect on the part of the organometallic groups. The donor effect of the 4-position does not appear to be completely negated however because the organometallic groups here retain a greater electron-withdrawing ability than the tert-butyl group, an effect which disappears in the 3-substituted compounds.

There has been considerable work in recent years on the problem of electron-withdrawal from aromatic rings by attached silicon- and germanium-containing substituents[12]. However the question still remains a controversial one. It is becoming apparent that much of the controversy results from the varying nature of the aromatic groups studied and the varying nature of the experimental conditions[12]. In this work [including the ν(N–O) results[2]] the changing experimental conditions for the various studies have caused a change in the electronic distribution in the pyridine *N*-oxide system, which particularly affects the donor nature of the 4-position of the ring. The result is an apparent change in the degree to which the attached silyl and germyl groups can behave as electron-withdrawing substituents.

EXPERIMENTAL

Materials

The 4-silyl- and 4-germyl-substituted pyridine *N*-oxides were prepared for the previous study[2]. 3-(Trimethylsilyl)pyridine *N*-oxide has been previously reported[13] and was prepared by the published method. 3-(Trimethylgermyl)pyridine *N*-oxide (b.p. 125°/0.4 mm) was prepared for the first time by the same method. Its purity (as well as that of the silyl compound) was checked by NMR spectroscopy and elemental analysis. (Found: C, 45.16; H, 5.97; N, 6.56; $C_8H_{13}GeNO$ calcd.: C, 45.37; H, 6.19; N, 6.62%.) NMR ($CDCl_3$): τ 9.56 (s, 9, Me_3Ge), τ 2.51 (m, 2, $H_{\beta,\gamma}$), τ 1.65 (m, 2, H_α).

3-tert-Butyl-, 4-tert-butyl-, and 4-acetylpyridine *N*-oxides were prepared from the corresponding pyridines by the method of Ochiai[14]. 4-tert-Butylpyridine and 4-acetylpyridine were commercially available samples, while 3-tert-butylpyridine was prepared by the method of Essery and Schofield[15]. Pyridine *N*-oxide, 4-picoline *N*-oxide, and 4-methoxypyridine *N*-oxide were commercially available samples. The latter two compounds were purified by crystallization from ethanol/ether, while pyridine *N*-oxide was sublimed under vacuum before use. All the pyridine *N*-oxides were dried by pumping for at least several hours in the presence of P_2O_5 before being used in each of the studies.

Spectroquality carbon tetrachloride and reagent grade methylene chloride were stored over Linde 4-A molecular sieves. Spectroquality methanol was stored over Drierite, and phenol was sublimed under vacuum before use.

pK_a determinations

The spectra of the pyridine *N*-oxides (ca. 5×10^{-5} *M* solutions) were determined with a Cary 14 recording spectrophotometer using matched 1 cm cells. The acid form was generated using 50% (v/v) sulfuric acid, while the free base spectra were obtained using neutral solutions[16]. Successive amounts of sulfuric acid were added to the solutions of free base to obtain at least three solutions of different acid–base form ratios· From the extinction coefficients measured at 256 nm, and the hydrogen ion concentrations determined by titration, the results were obtained using a standard calculation[17]. All spectra were measured at 24–28°, and it was found that the results did not change appreciably as the temperature was varied within this range. The pK_a values were reproducible to within ± 0.04 pK units.

Determination of $\Delta\nu(O-H)$

Measurements were carried out with a Perkin–Elmer 621 infrared spectrophotometer, using a 6 mm cell. Before each determination, the spectrum of the stock solution of methanol in carbon tetrachloride was obtained in order to check for the presence of water, which results in a broad band at 3300–3500 cm^{-1}. An acceptable methanol solution showed only a base line in the region in which the hydrogen-bonded ν(O–H) would appear. The pyridine *N*-oxide was then added to the methanol solution and the spectrum obtained. All manipulations of the pyridine *N*-oxides and the methanol solutions were carried out in a nitrogen-filled glove bag.

The pyridine *N*-oxide concentrations were ca. 0.015 *M*, while the concentration of the methanol solutions were 0.04 *M*. A brief study on 4-tert-butylpyridine *N*-oxide in which the methanol/base molar ratio was varied between 3/1 and 1/3 yielded no appreciable change in results. The value of $\Delta\nu$(O–H) given here for pyridine *N*-oxide (280 cm^{-1}) compares favorably with the value obtained by Shindo[9] (285 cm^{-1}), who used a methanol/base molar ratio of 1/2. The measurements were carried out at a room temperature of ca. 25°.

Determination of chemical shifts

The NMR spectra were obtained with a Varian Associates A-60 spectrometer. The chemical shifts were all recorded relative to the internal standard tetramethylsilane. The temperature (29°±1°) was determined using a methanol solution and calibration data supplied by Varian Associates.

The pyridine *N*-oxides were weighed in NMR tubes and enough stock solution of phenol in methylene chloride was added to make the solutions 1 *M* in pyridine *N*-oxide. All manipulations were carried out in a nitrogen-filled glove bag. A phenol concentration of 0.1 *M* was used since it had previously been shown[10] that the chemical shift value obtained with a phenol solution of this concentration was not far from the value associated with monomeric phenol. Although the phenol chemical shift value moves downfield as the base/phenol molar ratio increases (more complete complexation of the phenol), the value did not appear to change appreciably at base/phenol molar ratios greater than 10/1.

REFERENCES

1 E. Ochiai, *Aromatic Amine Oxides*, Elsevier, Amsterdam, 1967, Chapter 4.
2 M. A. Weiner, *J. Organometal. Chem.*, 23 (1970) C20.
3 R. G. Garvey, J. H. Nelson and R. O. Ragsdale, *Coord. Chem. Rev.*, 3 (1968) 375, and references therein; H. H. Jaffe and H. L. Jones, *Advan. Heterocycl. Chem.*, 3 (1964) 209, and references therein.
4 H. H. Jaffe and G. O. Doak, *J. Amer. Chem. Soc.*, 77 (1955) 4441.
5 J. M. Wilson, A. G. Briggs, J. E. Sawbridge, P. Tickle and J. J. Zuckerman, *J. Chem. Soc. A*, (1970) 1024.
6 R. S. Drago, N. O'Bryan and G. C. Vogel, *J. Amer. Chem. Soc.*, 92 (1970) 3924, and references therein.
7 D. W. Herlocker, R. S. Drago and V. I. Meek, *Inorg. Chem.*, 5 (1966) 2009.
8 J. H. Nelson, L. C. Nathan and R. O. Ragsdale, *J. Amer. Chem. Soc.*, 90 (1968) 5754.
9 H. Shindo, *Chem. Pharm. Bull.*, 7 (1959) 791.
10 D. P. Eyman and R. S. Drago, *J. Amer. Chem. Soc.*, 88 (1966) 1617.
11 E. A. Allen and L. W. Reevers, *J. Phys. Chem.*, 66 (1962) 613; I. Granacher, *Helv. Phys. Acta*, 34 (1961) 272.
12 C. J. Attridge, *Organometal. Chem. Rev., Sect. A*, 5 (1970) 323; E. A. V. Ebsworth, in A. G. MacDiarmid (Ed.), *Organometallic Compounds of the Group IV Elements*, Vol. 1, Part 1, Marcel Dekker, New York, 1968, pp. 82–88; see also: D. E. Fenton and J. J. Zuckerman, *Inorg. Chem.*, 7 (1968) 1323.
13 Y. Sukata, K. Adachi, Y. Akahori and E. Hayashi, *Yakugaku Zasshi*, 87 (1967) 1374; *Chem. Abstr.*, 68 (1968) 59649a.
14 E. Ochiai, *J. Org. Chem.*, 18 (1953) 534.
15 J. M. Essery and K. Schofield, *J. Chem. Soc.*, (1960) 4953.
16 H. H. Jaffe and G. O. Doak, *J. Amer. Chem. Soc.*, 77 (1955) 4451.
17 C. N. R. Rao, *Ultraviolet and Visible Spectroscopy*, Butterworths, London, 1961, pp. 75–77.