APPLICATION OF GAS CHROMATOGRAPHIC HEADSPACE ANALYSIS TO THE DETERMINATION OF IONIZATION CONSTANTS OF ORGANIC BASES IN COMPLEX MIXTURES

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SUMMARY

The possibility of using gas chromatographic headspace analysis in the determination of ionization constants of organic bases in complex mixtures is considered. A method for the determination of the ionization constant of an organic base which is represented in the chromatogram as an unresolved peak together with a neutral compound is proposed and the limits of its applicability are discussed.

INTRODUCTION

It was pointed out in an earlier paper[1] that the measurement of the ratio of either the areas or the heights of peaks A_B and A_B' for free bases in the vapour chromatograms of solutions with known concentrations of hydrogen ions $[H^+]$ and $[H^+]'$ makes it possible to determine ionization constants for volatile organic bases. When $[H^+] > [H^+]'$

$$K = \frac{\dfrac{A_B}{A_B'} \cdot [H^+] - [H^+]'}{1 - \dfrac{A_B}{A_B'}} \qquad (1)$$

The possibilities of the above method are developed in this paper into a procedure for the determination of the basicity constants for the components in a complex mixture of unknown composition, *i.e.*, for making measurements of K under conditions for which other methods are unsuitable. The proposed technique makes it possible to determine ionization constants even when the base under study gives a single peak with another component of the mixture in the chromatogram.

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THEORETICAL

If a base and a substance of neutral nature are represented in the chromatogram by a single, unresolved peak, the balancing equation can be written in a manner similar to that for an individual base[1]:

$$[B_g^M]V_g + ([B] + [BH^+] + [N])V_l = [B_g^M]'V_g + ([B]' + [BH^+]' + [N])V_l \quad (2)$$

where V_g and V_l are the gas and liquid phase volumes, $[N]$ is the concentration of the neutral substance in the solution, $[B_g^M]$ and $[B_g^M]'$ are the total concentrations of the components making up a single peak in the gas phase equilibrated with the solution with hydrogen ion concentrations of $[H^+]$ and $[H^+]'$, $[B]$ and $[B]'$ are the free base concentrations in the solutions with these two hydrogen ion concentrations, respectively, and $[BH^+]$ and $[BH^+]'$ are the concentration of the acid conjugated with the base in the respective solutions.

Substituting $[BH^+]$ and $[BH^+]'$ into eqn. 2 from the following expression:

$$K = \frac{[B][H^+]}{[BH^+]} = \frac{[B]'[H^+]'}{[BH^+]'}$$

and taking into consideration that the concentration of the substances in the gas phase is determined as a total concentration of the base, $[B_g]$, and the neutral compound, $[N_g]$, we can derive an equation that can be solved for K. However, this expression for K is complex, and a simpler one can be obtained when the following conditions are fulfilled:

(1) equal volumes of the vapour samples at different pH values of the solutions are subjected to analysis;

(2) the detector response is within its linear range; and

(3) the partition coefficient of the free base is much greater than the ratio V_g/V_l.

The ionization constant can then be calculated by the equation

$$K = \frac{[H^+](A_M/A_M' - A_N/A_M') - [H^+]'(1 - A_N/A_M')}{1 - A_M/A_M'} \quad (3)$$

where A_M and A_M' are peak areas or peak heights of the mixture in the gas phase equilibrated with a solution with hydrogen ion concentrations of $[H^+]$ and $[H^+]'$, and A_N is the area or height of a neutral substance peak (determined by gas phase analysis above the strongly acidified solution, i.e., when pH $<$ ($pK - 2$).

EXPERIMENTAL

Commercial acetone, toluene and ethanol were used. Commercial amines, pyridine and piperidine were additionally purified by distillation in a rectification column. The total amine concentration of their aqueous solutions was less than 0.5%. The concentration of ethanol in all solutions was 0.05%.

The pH values of the solutions were fixed by adding very small portions of

concentrated hydrochloric acid or concentrated potassium hydroxide solution and were controlled with an ECL-63-07 electrode (working range 0.5–13 pH units).

The gas samples were analysed at 100° on a Tsvet-136 chromatograph with a flame-ionization detector. Glass columns of length 2 m and I.D. 3 mm were used. The packing of the columns was 28% Pennwalt 223 + 4% potassium hydroxide on Gas-Chrom R, 80–100 mesh. The carrier gas was argon at a flow-rate of 80 ml/min.

Equilibrium was established at 25 ± 0.1° in a variable-volume device (100 ml) which was described in detail earlier[2].

The equilibrated gas phase was injected into the chromatographic column by means of a gas sample valve thermostated at 130°. The technique is described in detail elsewhere[3].

The peak areas were measured with a Takeda Riken TR-2213 digital integrator.

RESULTS AND DISCUSSION

In earlier work[1], we checked experimentally the validity of eqn. 1 for invidual bases. Eqn. 1 does not contain any concentration parameters of the bases under study, and therefore the influence of the other substances in the mixture is of little importance. On the other hand, the choice of $[H^+]$ and $[H^+]'$ is very important when the accurate determination of ionization constants is required.

The optimal pH values can be found from the expression for the relative error of K measurements derived from eqn. 1. A'_B can be measured with minimal error for pH' values in the range pH' > (pK + 2), where the area or the height of the peak is maximal and practically does not depend on the acidity of the solution. The desirable pH range is between (pK − 1) and (pK + 0.25).

The possibility of determining the pK values of bases in complex mixtures is illustrated by the example of a mixture of four aliphatic amines with pyridine and piperidine. Ethanol was added to the mixture as a neutral substance in the working pH range. The chromatograms of the vapour above the solution of the mixture under study at different pH values are shown in Fig. 1 to illustrate the quality of the separation of the mixture partition and the variation in the area of the peaks of the components.

The results obtained in this instance (Table I) show that the maximum absolute error does not exceed 0.25 pK unit. The error of the final result calculated on the basis of the peak height is somewhat greater than that calculated on the basis of the peak area. This can be attributed to some peak asymmetry of nitrogen-containing bases in the chromatograms. Such an accuracy is sufficient for the froup identification of aliphatic and aromatic amines and for other bases.

Ionization constants can also be determined graphically from the graph of A_B/A'_B of the base under analysis in the vapour versus the pH of the solution. In this instance the pK value is equal to the pH at A_B/A'_B = 0.5 (Fig. 2).

Pyridine–toluene and triethylamine–acetone mixtures were used to verify experimentally eqn. 3 (Table I). The pK values obtained for pyridine and triethylamine for both the individual peaks of the bases and the bases in mixtures with a neutral substance are virtually identical. When determining the pK value of a base represented in the chromatogram as a single peak with a neutral substance, the
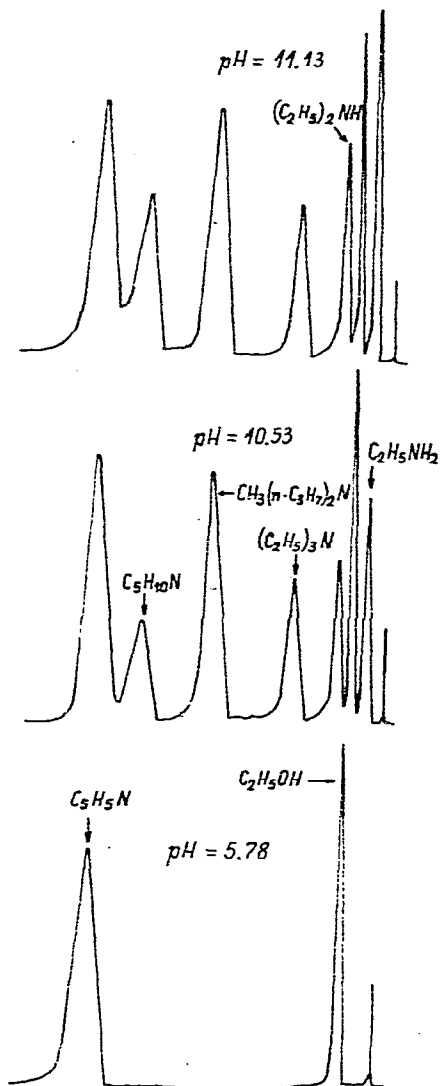
Fig. 1. Chromatograms of the vapours equilibrated with aqueous solutions of mixture of nitrogen-containing bases and ethanol at different pH values of the solution.

error would depend not only on the values of the quantities in eqn. 1 but also on the error in the peak area measurement of the neutral compound and on its proportion in the binary mixture with the base in the gas phase. The greater this proportion, the lower is the accuracy. The analysis of the cumbersome expression obtained by differentiation of eqn. 3 shows that the proportion of the neutral substance must be less than 0.25 at the maximum difference in the pH values (*ca.* 3) of the solutions under study and the errors in the measurement of peak areas or heights must be less than 1 % in order to ensure that the accuracy of the final result is of the order of a few percent.

In this instance, pK values can also be determined graphically from the plot of

TABLE I

pK VALUES OF NITROGEN-CONTAINING BASES IN MIXTURE DETERMINED BY GAS CHROMATOGRAPHIC HEADSPACE ANALYSIS

The results given are averages of 5–10 replicates.

Compound	pK				
	Literature data (I)	Calculated		Absolute error	
		By areas (II)	By heights (III)	By areas (II − I)	By heights (III − I)
Triethylamine	10.72 (ref. 4)	10.97	10.98	+0.25	+0.26
		10.90*	10.94*	+0.18	+0.22
Pyridine	5.25 (ref. 5)	5.45	5.43	+0.20	+0.18
		5.47*	5.43*	+0.22	+0.18
Methyldi-n-propylamine	—	10.64	10.63	—	—
Ethylamine	10.68 (ref. 4)	10.88	10.92	+0.20	+0.24
Diethylamine	11.02 (ref. 4)	11.23	11.30	+0.21	+0.28
Piperidine	11.12 (ref. 4)	11.24	11.28	+0.12	+0.16

* Values calculated using eqn. 3 for triethylamine represented in the chromatogram as a single peak with acetone and for pyridine represented as a single peak with toluene. The A_N values for acetone and toluene were found at pH 6.2 and 1.7, respectively.

A_M/A'_M versus the pH of the solutions under study; the pK value is equal to the pH at $A_M/A'_M = (1 - A_N/A'_M)/2$. The value of the ionization constant for triethylamine determined in such a manner is 10.85 (Fig. 3), which is 0.05 pK unit less than the value calculated by eqn. 3.

When two bases form a single peak in the chromatogram, the pH values of the individual bases can be found from the plot of A_M/A'_M versus pH; the pK_1 value is
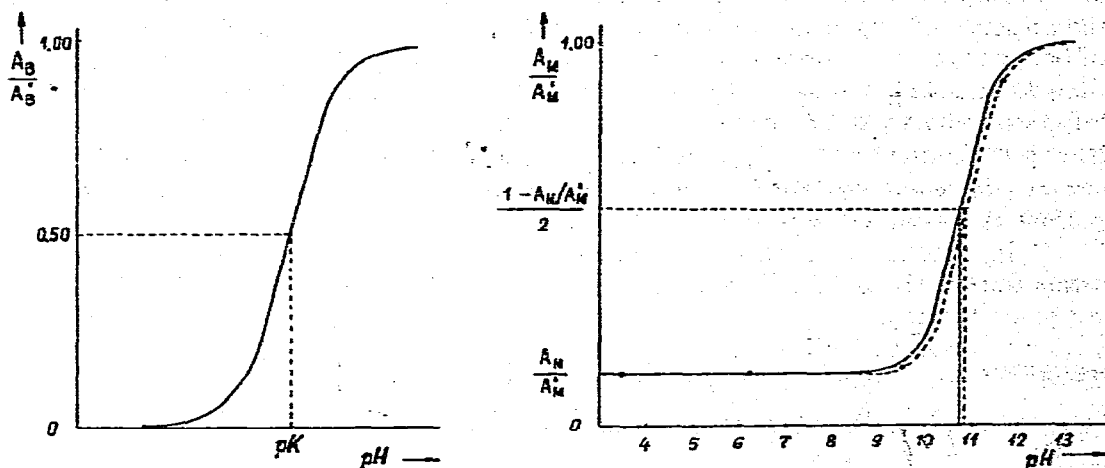

Fig. 2. Plot of the dependence of A_B/A'_B in vapours on the pH of the solution for an individual base (schematic).

Fig. 3. Plot of the dependence of A_M/A'_M in vapours on the pH of the solution for a mixture of triethylamine and acetone represented in the chromatogram as a single peak. $A_N/A'_M = 0.1378$. Continuous line, theoretical curve (eqn. 3); broken line, experimental curve.
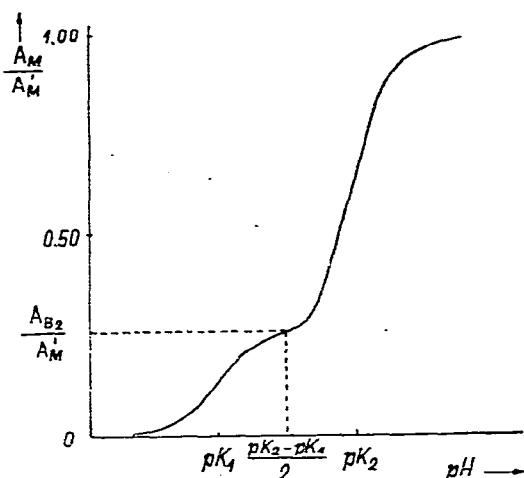
Fig. 4. Plot of the dependence of A_M/A'_M in vapours on the pH of the solution for a mixture of two bases represented in the chromatogram as a single peak (schematic). $pK_2 - pK_1 = 2.5$; $A_{B_2}/A'_M = 0.25$.

equal to the pH at $A_M/A'_M = (A_{B_2}/A'_M)/2$ and $pK_2 = $ pH at $A_M/A'_M = (1 - A_{B_2}/A'_M)/2$ (Fig. 4).

In addition to the applications mentioned, the suggested method can be used for the quantitative analysis of the components of unresolved peaks and for establishing the individuality of chromatographic peaks. Such an analysis can be carried out if at least one of the two substances in the single peak has acid–base properties.

In order to distinguish the components of an unresolved peak of a base and a neutral substance, the vapour above an appropriately basified or acidified solution of the sample under study should be analysed. A clear inflexion in the peak, indivating the presence of two bases, with an accuracy of the peak area or height measurements of better than 1 %, is observed at $(pK_2 - pK_1) > 2.5$ (Fig. 4). The large differences in the pK values of the two components of the plot that are necessary in order for an inflexion to be observed on the peak limit the possibilities of this approach for establishing the individuality of the peaks of the bases. The method of headspace analysis can be applied to pyridine and aliphatic amines with the columns used in the experiments described here.

In conclusion, it should be mentioned that a similar approach permits the estimation of the pK values not only of bases but also of volatile, acidic substances.

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