

# Self-Consistent Spectrophotometric Basicity Scale in Acetonitrile Covering the Range between Pyridine and DBU

Ivari Kaljurand,<sup>†</sup> Toomas Rodima,<sup>†</sup> Ivo Leito,<sup>†</sup> Ilmar A. Koppel,<sup>\*,†</sup> and Reinhard Schwesinger<sup>‡</sup>

*Institute of Chemical Physics, Department of Chemistry, University of Tartu, Jakobi 2, 51014 Tartu, Estonia, and Chemisches Laboratorium, Institut für Organische Chemie und Biochemie, Universität Freiburg, Albertstrasse 21, D-79104 Freiburg, Germany*

ilmar@chem.ut.ee

Received May 24, 2000

A self-consistent spectrophotometric basicity scale in acetonitrile, including DBU, ten (arylimino)-tris(1-pyrrolidinyl)phosphoranes, two (arylimino)tris(dimethylamino)phosphoranes, 2-phenyl-1,1,3,3-tetramethylguanidine, 1-(2-tolyl)biguanide, benzylamine, two substituted benzimidazoles, pyridine, and ten substituted pyridines, has been created. The span of the scale is almost 12  $pK_a$  units. Altogether, 29 different bases were studied and 53 independent equilibrium constant measurements were carried out, each describing the relative basicity of two bases. The scale is anchored to the  $pK_a$  value of pyridine of 12.33 that has been measured by Coetzee et al. Comparison of the basicity data of phenyliminophosphoranes and phenyltetramethylguanidines implies that the P=N bond in the (arylimino)tris(1-pyrrolidinyl)phosphoranes involves contribution from the ylidic (zwitterionic) structure analogous to that found in phosphorus ylides.

## Introduction

Neutral organic bases have found a wide field of applications in organic synthesis as reagents in base-mediated transformations and are often irreplaceable.<sup>1,2</sup> Compared to ionic bases, they have many substantial advantages, such as milder reaction conditions, the enhanced reactivity of the more naked anions in the poorly associating ion pairs formed, and better solubility.<sup>3–5</sup> Several new and very promising families of strong neutral bases, “proton sponges”,<sup>6,7</sup> guanidines,<sup>8</sup> amidines, phosphazenes,<sup>3–5,9</sup> and phosphorus ylides,<sup>10,11</sup> have emerged.

Exact quantitative basicity data are very important in applying bases in various fields of chemistry and in designing new bases with desired properties. Although a vast amount of acid–base data has been collected,<sup>12–14</sup> the situation is still far from ideal.

The intrinsic basicity can be measured in gas-phase experiments or calculated in simpler cases. Up to the present much gas-phase basicity data<sup>12</sup> have been collected. However, in this field there is enough space for improvement; basicities of only a few superbases (by definition the superbases have  $GB$  (gas-phase basicity) over 239 kcal/mol)<sup>9</sup> have been determined. The reasons are the lack of suitable reference bases,<sup>15</sup> low volatility of strong bases, long stabilization periods, and tendency of strong bases to undergo fragmentation in the experiments.

In condensed media investigation of basicities of strong bases has some limitations. The acid strength of solvent, various association processes, and decomposition of base or solvent are only some of the effects that have to be considered while measuring the basicities in condensed media. In relatively acidic media (such as water) strong bases are leveled up and only the basicity of moderately strong bases can be reliably measured. Alcohols have also been common solvents for such studies.<sup>13</sup> Stronger bases can be reliably investigated in solvents that have lower acidity and are relatively inert if exposed to the bases. In such solvents the basicities are not leveled and the intrinsic properties of bases are expressed to a higher

\* Ph: (+372-7) 375 263. FAX: (+372-7) 375 264.

<sup>†</sup> University of Tartu.

<sup>‡</sup> Universität Freiburg.

(1) *Encyclopedia of Reagents for Organic Synthesis*; Paquette, L. A., Ed.; J. Wiley & Sons: Chichester, 1995.

(2) Oediger, H.; Möller, F.; Eiter, K. *Synthesis* **1972**, 591–598.

(3) Schwesinger, R.; Schlemper, H.; Hasenfratz, C.; Willaredt, J.; Dambacher, T.; Breuer, T.; Ottaway, C.; Fletschinger, M.; Boele, J.; Fritz, H.; Putzas, D.; Rotter, H. W.; Bordwell, F. G.; Satish, A. V.; Ji, G.-Z.; Peters, E.-M.; Peters, K.; von Schnering, H. G.; Walz, L. *Liebigs Ann.* **1996**, 1055–1081 and references therein.

(4) Schwesinger, R.; Willaredt, J.; Schlemper, H.; Keller, M.; Schmitt, D.; Fritz, H. *Chem. Ber.* **1994**, 127, 2435–2454 and references therein.

(5) Tang, J.; Dopke, J.; Verkade, J. G. *J. Am. Chem. Soc.* **1993**, 115, 5015–5020 and references therein.

(6) (a) Llamas-Saiz, A. L.; Foces-Foces, C.; Elguero, J. *J. Mol. Struct.* **1994**, 328, 297–323 and references therein. (b) Brzezinski, B.; Schroeder, G.; Grech, E.; Malarski, Z.; Sobczyk, L. *J. Mol. Structure.* **1992**, 274, 75–82.

(7) Koppel, I. A.; Koppel, J. B.; Pihl, V. O. *Org. React.* **1987**, 24, 387–398.

(8) Leffek, K.; Przuszyński, P.; Thanapaalasingham, K. *Can. J. Chem.* **1989**, 67, 590–595.

(9) Raczynska, E. D.; Decouzon, M.; Gal, J.-F.; Maria, P.-C.; Wozniak, K.; Kurg, R.; Carins, S. N. *Trends Org. Chem.* **1998**, 7, 95–103 and references therein.

(10) Johnson, A. W. (with special contributions by Kaska, W. C.; Starzewski, K. A. O.; Dixon, D. A.) *Ylides and Imines of Phosphorus*; Wiley: New York, 1993.

(11) Goumri-Magnet, S.; Guerret, O.; Gornitzka, H.; Cazaux, J. B.; Bigg, D.; Palacios, F.; Bertrand, G. *J. Org. Chem.* **1999**, 64, 3741–3744 and references therein.

(12) Hunter, E. P. L.; Lias, S. G. *J. Phys. Chem. Ref. Data* **1998**, 27, 413–656.

(13) *Tables of Rate and Equilibrium Constants of Heterolytic Organic Reactions*; Palm, V. Ed.; VINITY: Moscow-Tartu, 1975–1985.

(14) Izutsu, K. *Acid–Base Dissociation Constants in Dipolar Aprotic Solvents*; IUPAC Chemical Data Series No. 35; Blackwell Scientific: Oxford, 1990.

(15) Raczynska, E. D.; Maria P.-C.; Gal, J.-F.; Decouzon, M. *J. Phys. Org. Chem.* **1994**, 7, 725–733 and references therein.

extent. Several solvents, including dimethyl sulfoxide, acetonitrile (AN), THF, etc., have found wide application as media for studies of strong bases, and a vast number of papers and several compilations have been published.<sup>13,14</sup> Although AN has been probably the most popular solvent among the above-mentioned and a vast number of basicity measurements in AN have been carried out, the situation is still not good. Basicity data obtained by different authors even by the same method often lack consistency and are rather with gaps. Even for well studied pyridines included in this work the measured values deviate often by up to one or more  $pK_a$  units. That is more than stated with the experimental errors (see below for examples).

Our aim was to improve the situation in this field by building a reliable continuous self-consistent and sufficiently wide spectrophotometric basicity scale in AN covering the range from 12 to 24  $pK_a$  units.

Basicity of a base B in solvent S is defined using eq 1



$$K_a = \frac{a(HS^+) \cdot a(B)}{a(HB^+)} \quad (2)$$

and is expressed as dissociation constant  $K_a$  of the conjugate acid  $HB^+$  of the base B or more commonly its negative logarithm  $pK_a$ .

AN has some advantages over other aprotic solvents as a medium for acid–base studies. It is a very weakly basic and acidic dipolar aprotic solvent with high dielectric constant (36.0<sup>16</sup>) and hence favors the dissociation of ion pairs into free ions. The autoprotolysis constant  $K_{auto}$  of AN is very low:  $pK_{auto} \geq 33$ ,<sup>17</sup> (even values of  $pK_{auto}$  as high as 44 have been suggested<sup>18,19</sup>), and this makes it a good differentiating solvent.

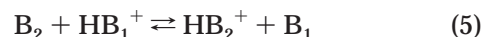
Because AN solvates ions more weakly than water, various association processes have to be considered.<sup>16,20</sup> These processes may have an important role in explaining the fact that different results are obtained with different methods and conditions by different authors. AN is a weak electron-pair donor and hence solvates cations better than anions.<sup>16,21</sup> Therefore the main association processes, homoconjugation (eq 3) and heteroconjugation (eq 4) are not as extensive as in systems



involving anions.<sup>22</sup> It is generally observed that homoconjugation increases with an increasing number of acidic hydrogen atoms, and also poor steric hindrance of the protonation center is a source of increased homoconju-

gation.<sup>23</sup> The easiest way to decrease the influence of the association processes to a negligible extent (they are always an additional source of poorer accuracy) is to use methods that allow the use of very dilute solutions. The UV–vis spectrophotometric method employed in the present work has the advantage over many others methods (potentiometry, <sup>13</sup>C NMR spectroscopy, etc.) that in certain cases ( $\pi$ -electron-rich systems conjugated with acidity center) sufficiently low concentrations of solutes may be used to minimize hetero- and homoconjugation processes.

To exclude the necessity for measuring the hydrogen ion activity (see eq 1) we studied the equilibrium between two bases  $B_1$  and  $B_2$ :



The relative basicity,  $\Delta pK_a$ , of  $B_1$  and  $B_2$  was found as described elsewhere:<sup>24,25</sup>

$$\Delta pK_a = pK_a(HB_2^+) - pK_a(HB_1^+) = \log \frac{a(HB_2^+) \cdot a(B_1)}{a(HB_1^+) \cdot a(B_2)} \quad (6)$$

The method consists of UV–vis spectrophotometric titration of a solution, where both of the bases are present, with an optically transparent acid or base.

## Experimental Section

**Chemicals.** The (arylimino)tris(1-pyrrolidinyl)phosphoranes **2–4**, **6**, **8**, **9**, **12**, **13**, **15**, and **22** were synthesized and purified as described elsewhere.<sup>26</sup> 2-Phenyl-1,1,3,3-tetramethylguanidine **7** was synthesized as described in ref 8. 2-Methylpyridine **28** (REAKHIM) was distilled fractionally from KOH in the atmosphere of dry argon. 2,4,6-trimethylpyridine **21** (REAKHIM) was distilled fractionally from KOH under reduced pressure. 4-methoxypyridine **25** (Aldrich, 97%) was distilled fractionally from  $MgSO_4$  under reduced pressure, and 2,6-dimethylpyridine **27** (REAKHIM) was distilled fractionally from BaO under reduced pressure. Benzylamine **17** (REAKHIM, "pure") was kept on NaOH overnight and distilled from it fractionally under reduced pressure. 1-(2-Tolyl)biguanide **10** (Aldrich, 98%), 4-aminopyridine **16** (Aldrich, 98%), 2,3-diaminopyridine **20** (Aldrich, 98%), and 2-aminopyridine **24** (REAKHIM, "pure for analysis") were recrystallized from ethanol. 2-Amino-1-methylbenzimidazole **18** (Aldrich, 95%) and 2-aminobenzimidazole **19** (Aldrich, >97%) were recrystallized once from ethanol and then from water. DBU **1** (Aldrich, 98%), 4-(dimethylamino)pyridine **14** (TCL, >99%), 2,6-diaminopyridine **23** (Aldrich, 99+%), 3-aminopyridine **26** (Aldrich, 99%), and pyridine **29** (Fluka, >99.8%) were used without additional purification. (Phenylimino)tris(dimethylamino)phosphazene **5** was synthesized according to the procedure described in ref 5. The same procedure was employed for synthesis of (2-chlorophenylimino)tris(dimethylamino)phosphorane **11** (starting compounds: 2-Cl-C<sub>6</sub>H<sub>4</sub>-N<sub>3</sub><sup>27,28</sup> and (Me<sub>2</sub>N)<sub>3</sub>P (Fluka)). The crude product (a brown oil) was distilled to give a yellowish oil (yield 65%, bp 137 °C (0.15 Torr)). Anal. Calcd for C<sub>12</sub>H<sub>22</sub>N<sub>4</sub>P: C, 49.93; H, 7.68; N, 19.40. Found: C, 49.52;

(16) Coetzee, J. F. *Prog. Phys. Org. Chem.* **1967**, 4, 45–92 and references therein.

(17) Kolthoff, I. M.; Chantooni, M. K., Jr. *J. Phys. Chem.* **1968**, 72, 2270–2272.

(18) Schwesinger, R.; Schlemper, H. *Angew. Chem., Int. Ed. Engl.* **1987**, 26, 1167–1169.

(19) Bernasconi, C. M.; Leyes, A. E.; Ragains, M. L.; Shi, Y.; Wang, H.; Wulff, W. D. *J. Am. Chem. Soc.* **1998**, 120, 8632–8639.

(20) Magoński, J.; Rajzer, B. *J. Chem. Soc., Perkin Trans. 2* **2000**, 1181–1185.

(21) Reichardt, C. *Solvents and Solvent Effects in Organic Chemistry*, 2nd ed.; VCH: Weinheim, 1988.

(22) Coetzee, J. F.; Padmanabhan, G. R.; Cunningham, G. P. *Talanta* **1964**, 11, 93–103.

(23) Coetzee, J. F.; Padmanabhan, G. R. *J. Am. Chem. Soc.* **1965**, 87, 5005–5010.

(24) Leito, I.; Kaljurand, I.; Koppel, I. A.; Yagupolskii, L. M.; Vlasov, V. M. *J. Org. Chem.* **1998**, 63, 7868–7874.

(25) Leito, I.; Rodima, T.; Koppel, I. A.; Schwesinger, R.; Vlasov, V. M. *J. Org. Chem.* **1997**, 62, 8479–8483.

(26) Rodima, T.; Mäemets, V.; Koppel, I. A. *J. Chem. Soc., Perkin Trans. 1* **2000**, 2637–2644.

(27) Spauschus, H. O.; Scott, J. M. *J. Am. Chem. Soc.* **1951**, 73, 208–210.

(28) Bullock, M. W.; Hand, J. J. *J. Am. Chem. Soc.* **1956**, 78, 5854–5857.

H, 8.02; N, 18.88.  $^1\text{H}$  NMR (200 MHz,  $\text{CH}_3\text{CN}$ )  $\delta$  2.66 (d,  $^3J_{\text{P-H}} = 9.6$  Hz, 18H), 6.48 (dddd,  $^3J_{\text{H-H}} = 7.8$  Hz,  $^3J_{\text{H-H}} = 7.2$  Hz,  $^4J_{\text{H-H}} = 1.7$  Hz,  $^6J_{\text{P-H}} = 0.6$  Hz, 1H), 6.73 (ddd,  $^3J_{\text{H-H}} = 8.0$  Hz,  $^4J_{\text{H-H}} = 1.7$  Hz,  $^4J_{\text{P-H}} = 1.1$  Hz, 1H), 6.94 (ddd,  $^3J_{\text{H-H}} = 7.2$  Hz,  $^3J_{\text{H-H}} = 8.0$  Hz,  $^4J_{\text{H-H}} = 1.7$  Hz, 1H), 7.17 (ddd,  $^3J_{\text{H-H}} = 7.8$  Hz,  $^4J_{\text{H-H}} = 1.7$  Hz,  $^5J_{\text{P-H}} = 2.5$  Hz, 1H);  $^{13}\text{C}$  NMR (50 MHz,  $\text{CH}_3\text{CN}$ )  $\delta$  37.7 ( $^2J_{\text{P-C}} = 3.3$  Hz), 117.3, 123.7 ( $^3J_{\text{P-C}} = 7.2$  Hz), 127.9, 128.2 ( $^3J_{\text{P-C}} = 21$  Hz), 130.0, 149.1 ( $^2J_{\text{P-C}} = 8.8$  Hz).

Solutions of trifluoromethanesulfonic acid (TfOH) (Aldrich, 99+%) and (ethylimino)tris(1-pyrrolidinyl)phosphorane (EtP<sub>1</sub>-(pyrr)) were used as acidic and basic titrant, respectively. Synthesis and purification of the latter one has been described earlier.<sup>4</sup> EtP<sub>1</sub>(pyrr) was fractionally distilled from BaO under reduced pressure and stored under dry argon.

**Solvent.** AN (>99.9%, Super Purity Solvent (far UV), water content < 0.005%) was purchased from Romil (Cambridge, U.K.) and was used without further purification. It was stored in dark bottles in a desiccator over P<sub>2</sub>O<sub>5</sub>. It has low absorbance in the UV region down to 200 nm, and its absorbance did not change upon addition of acidic or basic titrant.

**Experimental Setup.** A spectrophotometric titration method of previous works<sup>24,25</sup> was modified. As a result of the possible sensitivity of the bases to the moisture and oxygen, all weighing operations (except the weighing of TfOH for the standard acid solution), preparation of all solutions (all solutions were made daily), titration, and spectrophotometric measurements were carried out in a glovebox in an atmosphere of dry nitrogen. For continuous drying and purifying of the atmosphere in the glovebox from volatile basic and acidic contaminants, we used molecular sieves (Aldrich, 4 Å), powdered P<sub>2</sub>O<sub>5</sub>, and KOH pellets. A Perkin-Elmer Lambda 2S spectrophotometer was equipped with an external sample compartment (ESC). The 2-m long quartz-fiber light conductor cables of the ESC were guided through the wall of the glovebox and fastened airtightly. The spectrophotometer cell was closed with a hollow PTFE stopper with PTFE/silicone septa and open-top screw cap. The acidic and basic titrants were added into the cell through the septa using Hamilton gastight microliter syringes. The concentrations of both titrants were in the mM range. We found that the syringe needles were resistant to 10<sup>-2</sup>–10<sup>-3</sup> M TfOH solution. A reference cell with pure AN was placed in the spectrophotometer cell holder. The concentrations of individual bases were usually in the 10<sup>-5</sup> M range, and their total concentration in our experiments never exceeded 2.2 × 10<sup>-4</sup> M.

The water content of the titrated solutions was determined to be between 0.9 and 2.4 mM by means of Karl Fischer titration. Temperature was kept at 25 ± 1 °C during the measurements.

**Calculation Methods.** From each titration experiment, the  $\Delta\text{p}K_{\text{a}}$  was determined as the mean of 5–30 values using the calculation methods described previously.<sup>24,25</sup> The essence of the general calculation method is the following. When two partially protonated bases B<sub>1</sub> and B<sub>2</sub> are in the same solution, then the following equation holds for absorbance *A* at wavelength  $\lambda$  (1 cm path length):

$$A^{\lambda} = [\text{HB}_1^+]\epsilon_{\text{HB}_1^+}^{\lambda} + [\text{B}_1]\epsilon_{\text{B}_1}^{\lambda} + [\text{HB}_2^+]\epsilon_{\text{HB}_2^+}^{\lambda} + [\text{B}_2]\epsilon_{\text{B}_2}^{\lambda} \quad (7)$$

The molar absorptivities  $\epsilon$  can be found separately from the spectra of the free bases and fully protonated bases. If we use concentrations that are normalized to 1 (see ref 25) then we may write  $[\text{HB}_1^+] = 1 - [\text{B}_1]$  and  $[\text{HB}_2^+] = 1 - [\text{B}_2]$ . After a mathematical transformation of eq 7 we get

$$\frac{A^{\lambda} - \epsilon_{\text{HB}_1^+}^{\lambda} - \epsilon_{\text{HB}_2^+}^{\lambda}}{(\epsilon_{\text{B}_2}^{\lambda} - \epsilon_{\text{HB}_2^+}^{\lambda})} = [\text{B}_1] \frac{(\epsilon_{\text{B}_1}^{\lambda} - \epsilon_{\text{HB}_1^+}^{\lambda})}{(\epsilon_{\text{B}_2}^{\lambda} - \epsilon_{\text{HB}_2^+}^{\lambda})} + [\text{B}_2] \quad (8)$$

If the spectra are recorded over a range of wavelengths then  $[\text{B}_1]$  and  $[\text{B}_2]$  can be found from eq 8 as the slope and intercept of a regression line. If  $[\text{B}_1]$  and  $[\text{B}_2]$  are known, the calculation of  $\Delta\text{p}K_{\text{a}}$  of the bases is straightforward. In many cases (e.g.,

when the bases have absorption maxima in different wavelength ranges) it was possible to use various simpler calculation procedures (see refs 24 and 25). As a rule, the results obtained using different calculation procedures agreed well. It was found that  $\Delta\text{p}K_{\text{a}}$  values over 2  $\Delta\text{p}K_{\text{a}}$  units could be reliably determined over different ranges of wavelengths only by methods that apply the least-squares of linear combinations method (see ref 25).

All bases used in this work and their conjugate acids have a significant difference in some region of their UV-vis spectra, and thus they can be treated as “visible” bases. Even DBU and benzylamine, which have maximum differences between absorbances of the neutral and protonated forms in a narrow region in UV, could be treated as “visible” bases.

## Results

All in all, 53 individual relative acid–base equilibrium measurements between 29 bases were carried out to give the continuous basicity scale presented in Table 1. The relative basicity of any two bases in the scale can be obtained by combining at least two independent sets of measurements. Multiple overlapping measurements make the results more reliable and help to estimate their self-consistency. The entire basicity range covered involves at least two independent pathways of measurements, and the relative basicity of any two bases can be obtained by combining at least two independent sets of measurements. Reversibility of the protonation/deprotonation process of all bases was checked. All equilibria were reached in minutes and were stable.

In AN, homo- and heteroconjugation reactions (see eqs 3 and 4) of bases must be taken into account if the concentration of solutes is higher than 10<sup>-3</sup> M or if the homoconjugation constant  $K_{\text{BHB}}$  is high.<sup>29</sup> Pyridines have a  $K_{\text{BHB}}$  in AN between 4 and 100;<sup>30,22,23</sup> benzylamine, 15;<sup>23</sup> and DBU, 35<sup>31</sup> L/mol. It is evident that phosphazene bases have lower homoconjugation constants as a result of their higher degree of charge delocalization and steric hindrance of the protonation center. In our experiments the concentration of the bases was usually 1.6 × 10<sup>-5</sup> M and never exceeded 1.2 × 10<sup>-4</sup> M. Therefore we assume that there was no need to consider homo- and heteroconjugation in the calculation procedures.

The method used in this work has the disadvantage that only relative basicities can be determined. To assign the absolute  $\text{p}K_{\text{a}}$  values for the conjugate acids of the bases, the scale has to be anchored to a reference compound or compounds for which the  $\text{p}K_{\text{a}}$  value(s) are known. Direct anchoring of the present scale to the “well-behaved” picric acid,<sup>24,32</sup> having a  $\text{p}K_{\text{a}}$  value that has been measured with great care, is probably not the best solution since it has a different charge type. In addition, the introduction of another anion (besides the TfO<sup>-</sup>) to the solution may have some effect on the  $\text{p}K_{\text{a}}$  values of bases through the possible difference in ion-pairing as compared to the TfO<sup>-</sup>. Minor influence of the counter-

(29) Kolthoff, I. M.; Chantooni, M. K., Jr.; Bhowmik, S. *Anal. Chem.* **1967**, *39*, 1627–1633.

(30) (a) Augustin-Nowacka, D.; Chmurzynski, L. *Anal. Chim. Acta* **1999**, *381*, 215–220. (b) Chmurzynski, L. *Anal. Chim. Acta* **1996**, *321*, 237–244. (c) Chmurzynski, L. *Anal. Chim. Acta* **1996**, *329*, 267–274. (d) Chmurzynski, L. *Pol. J. Chem.* **1991**, *65*, 1387–1396. (d) Chmurzynski, L.; Liwo, A. *J. Chem. Soc., Faraday Trans.* **1991**, *87*, 3853–3856.

(31) Galewski, W.; Jarczewski, A.; Stanczyk, M.; Brzezinski, B.; Bartl, F.; Zundel, G. *J. Chem. Soc., Faraday Trans.* **1997**, *93*, 2515–2518.

(32) Kolthoff, I. M.; Chantooni, M. K. Jr. *J. Am. Chem. Soc.* **1965**, *87*, 4428–4436.



**Table 1. Directly Measured Relative Basicity Values for Bases and Estimated Absolute  $pK_a$  Values for Their Conjugate Acids in AN**

$pK_a$	Directly measured $\Delta pK_a$	No.	Base
24.13		1	
23.69	0.45	2	
22.92	0.77	3	
22.15	0.74	4	
21.05	1.20	5	
21.03	1.55	6	
20.60	1.09	7	
20.40	2.54	8	
19.95	0.63	9	
19.43	0.42	10	
18.84	0.62	11	
18.35	0.44	12	
18.30	2.10	13	
17.74	1.59	14	
17.46	1.69	15	
17.40	0.46	16	
16.70	0.59	17	
16.11	2.20	18	
15.87	1.07	19	
15.03	0.06	20	
14.77	0.60	21	
14.68	0.93	22	
14.56	0.25	23	
14.26	0.90	24	
14.04	1.44	25	
13.96	0.91	26	
13.92	1.67	27	
13.11	0.08	28	
12.33	1.29	29	

anion on the basicity of bases has been observed for potentiometric (and conductometric) measurements at higher concentrations.<sup>23</sup> The dissociation constant for the pyridinium picrate ion pair was measured in AN and was found to be  $3.0 \times 10^{-3}$  mol/L;<sup>33</sup> this is sufficiently low to have some influence upon the acid–base equilibria. Anchoring the scale to some other neutral acid with highly delocalized charge in the anionic form and with reliably measured  $pK_a$  in AN (e.g., with 2-(pentafluoro-

phenyl)malono-1,3-dinitrile ( $pK_a$  in AN 13.01)<sup>24</sup> or 2-(2-perfluoronaphthyl)malono-1,3-dinitrile ( $pK_a$  in AN 12.23),<sup>24</sup> etc.) is also not preferred since these compounds are not very common and the ion-pairing reactions of these compounds have not been investigated. However, the majority of basicity values in AN given in the literature

(33) Chantooni, M. K., Jr.; Kolthoff, I. M. *J. Am. Chem. Soc.* **1968**, *90*, 3005–3009.

**Table 2. Basicity Values in AN Determined in This Work for Which There Are Corresponding Values Reported in the Literature**

base	$pK_a$ in AN		
	this work	literature	difference
<b>1</b>	24.13	23.9 <sup>a</sup> 24.33 <sup>b</sup>	+0.2 −0.20
<b>2</b>	23.69	23.9 <sup>c</sup>	−0.2
<b>3</b>	22.92	23.4 <sup>c</sup>	−0.5
<b>4</b>	22.15	22.6 <sup>c</sup>	−0.45
<b>5</b>	21.05	20.9 <sup>c</sup>	+0.15
<b>6</b>	21.03	21.0 <sup>c</sup>	0
<b>7</b>	20.60	20.6 <sup>a</sup>	0
<b>8</b>	20.40	20.7 <sup>c</sup>	−0.3
<b>9</b>	19.95	19.8 <sup>c</sup>	+0.15
<b>12</b>	18.35	18.0 <sup>c</sup>	+0.35
<b>13</b>	18.30	17.9 <sup>c</sup>	+0.4
<b>14</b>	17.74	18.18 <sup>d</sup>	−0.44
<b>15</b>	17.46	17.5 <sup>c</sup>	0
<b>16</b>	17.40	17.61 <sup>e</sup> 18.38 <sup>d</sup> 17.00 <sup>f</sup>	−0.21 −0.98 +0.40
<b>17</b>	16.70	16.76 <sup>g</sup>	−0.06
<b>19</b>	15.87	15.95 <sup>e</sup>	−0.08
<b>20</b>	15.03		
<b>21</b>	14.77	14.38 <sup>h</sup>	+0.39
<b>22</b>	14.68	14.5 <sup>c</sup>	+0.2
<b>23</b>	14.56		
<b>24</b>	14.26	14.66 <sup>d</sup> 14.43 <sup>e</sup>	−0.40 −0.17
<b>25</b>	14.04		
<b>26</b>	13.96	14.35 <sup>d</sup>	−0.39
<b>27</b>	13.92	14.41 <sup>d</sup>	−0.49
<b>28</b>	13.11	12.76 <sup>h</sup> 13.88 <sup>d</sup>	+0.35 −0.77
<b>29</b>	taken as 12.33	12.33 <sup>g</sup> 12.60 <sup>d</sup> 12.52 <sup>i</sup>	0 −0.27 −0.19

<sup>a</sup> Reference 8. <sup>b</sup> Reference 4, anchored to the  $pK_a$  value of 1,4-diaminobutane taken as 20.12. <sup>c</sup> Reference 26. <sup>d</sup> Reference 30a. <sup>e</sup> Reference 34b. <sup>f</sup> Reference 35c. <sup>g</sup> Reference 23. <sup>h</sup> Reference 36. <sup>i</sup> Reference 35d.

that have been obtained from potentiometric measurements have indirectly been measured relative to picric acid, because picrate buffers have commonly been used to calibrate the glass electrode.

Although the  $pK_a$  values in AN have been reported for several compounds (see Table 2) from the present scale there are often disagreements between the results from different authors that are higher than the stated experimental errors. For example, see compounds **16** and **28** in Table 2. Anchoring the scale to more than one point may distort the final results because some values are more influenced by possible erroneous values of anchoring points than others. Anchored to one point, all absolute values of the given scale are influenced to same extent, and relative values, calculated from the overlapping measurements, remain unaffected.

Criteria for the evaluation of the best anchoring point should be the correctness of the  $pK_a$  determination method, holding the principles of thermodynamics and reversibility and also considering the solutes activities and association processes. The number of parallel runs and consistency with results from other authors may also be criteria. Since in most works the potentiometric method was used, in which picrate buffers were used for the calibration of the glass-electrode, it would be predicted that the  $pK_a$  values near to the  $pK_a$  value of picric acid should be with the highest level of confidence. Analysis of the references concerning the basicity data

in AN given in Table 2 shows good consistency between relative basicities of some compounds, namely, for **7**, **17**, **19** and **29** determined by other authors and in this work (see Table 2).  $pK_a$  values for various substituted pyridines given in ref 30a in comparison with results from this work show also consistency between relative basicities with two exceptions, **16** and **28**.

On the basis of these considerations we decided to anchor our scale to the  $pK_a$  value of pyridine ( $pK_a = 12.33$ ) determined by Coetzee and Padmanabhan.<sup>23</sup>

The absolute  $pK_a$  values of the bases were calculated similarly as in a previous paper<sup>24</sup> by minimizing the sum of squares of differences between directly measured  $\Delta pK_a$  values and the assigned  $pK_a$  values, while keeping the  $pK_a$  value of pyridine constant and equal to 12.33. However, it should be stressed that the absolute  $pK_a$  values of bases given in Table 1 are not as accurate as the relative  $pK_a$ 's. One could anchor the scale to any other absolute  $pK_a$  value at one's own discretion; the relative basicities will remain the same. Precision  $s$  of the measurements was calculated as in ref 24;  $n_m = 53$ ,  $n_c = 29 - 1 = 28$ . For our results,  $s = 0.03$   $pK_a$  units.

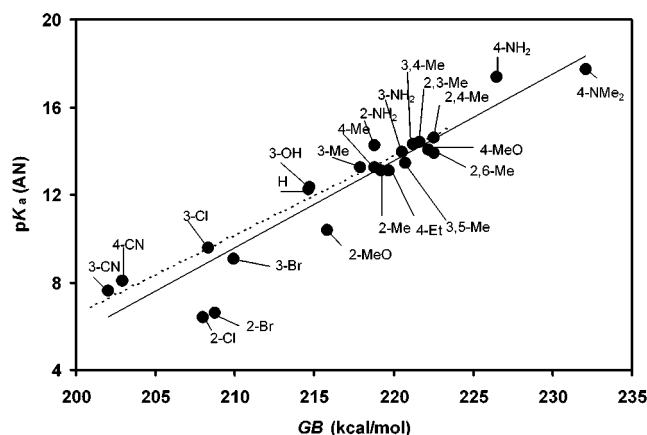
AN has the disadvantage that very strong bases tend to oligomerize this solvent.<sup>16,18</sup> The  $pK_a$  of the conjugated acid of EtP<sub>1</sub>(pyrr) in AN, the strongest base involved in our experiment, is reported to be 28.89,<sup>4</sup> being sufficiently low not to decompose the solvent in a short time but still sufficiently high to be able to deprotonate the conjugate acids of the bases under study. However, if the standard solution of EtP<sub>1</sub>(pyrr) was left to stand for several days, some discoloration of the solution was observed.

## Discussion

**Comparison of the Present  $pK_a$  Data with Those from the Literature.** For a number of bases investigated in this work there are also  $pK_a$  values available from the literature (Table 2).

For the aryliminophosphoranes the results of this work can be compared with earlier results obtained using <sup>13</sup>C NMR spectroscopy.<sup>26</sup> In the present work for several compounds new  $pK_a$  values, somewhat different from the ones from ref 26, were found. The advantages of the UV–vis spectrophotometric method over <sup>13</sup>C NMR spectroscopy are the higher obtainable precision (due to the larger number of indicator ratios used for the calculations to obtain  $\Delta pK_a$  of two compounds), larger measurable differences of  $pK_a$  values, and above all, the possibility to work with very dilute solutions that significantly minimizes the influence of various association processes on the results. Also, in the NMR study there were several cases when only one measurement of relative basicity was carried out for a given iminophosphorane base.

Analysis of the data concerning pyridines from Table 2 reveals that there are generally systematic differences between the  $pK_a$  values from different authors. This is not unexpected since potentiometry, which is the most exploited method for  $pK_a$  measurements, works well in aqueous media but has several problems (restrictions of electrode systems, association processes, variable activities of solutes, etc.) in nonaqueous media. The present work has seven coincident points with ref 30a. The mean systematic difference of −0.4  $pK_a$  units was observed between our  $pK_a$  values and the values from that work (see Table 2), with two exceptions, 4-aminopyridine and 2-methylpyridine, which differ markedly more. The value



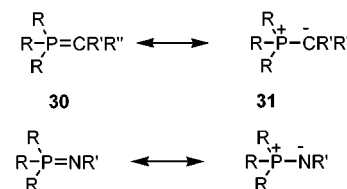
**Figure 1.** Correlation between gas-phase basicity (*GB*, 1 cal = 4.184 J) values and  $pK_a$  values in AN for pyridines. The solid line corresponds to the whole series of pyridines ( $pK_a(\text{AN}) = (-73.9 \pm 6.7) + (0.397 \pm 0.031) GB$ ;  $n = 23$ ;  $r^2 = 0.888$ ;  $s = 1.07$ ); the dotted line corresponds to the series of 3-substituted pyridines ( $pK_a(\text{AN}) = (-66.4 \pm 8.4) + (0.365 \pm 0.039) GB$ ;  $n = 6$ ;  $r^2 = 0.955$ ;  $s = 0.60$ ). The  $pK_a$  data for the pyridines not studied in this work have been taken from refs 30a, 35b, and 35d and have been corrected by adding  $-0.4$ ,  $-0.19$ , and  $-0.19$ , respectively in order to take into account the systematic differences between those refs and this work (see the discussion). The *GB* values have been taken from ref 12.

for the basicity of 4-aminopyridine in ref 30a is surprising, since in the present work, in water<sup>13</sup> and in the gas phase,<sup>12</sup> 4-(dimethylamino)pyridine is a stronger base than 4-aminopyridine; there should not be any specific interactions in AN that could shift the  $pK_a$  value in such a way. The present work has two coincident points with the ref 36, namely, **21** and **28**. The mean difference is  $+0.37$   $pK_a$  units.

Comparison of the  $pK_a$  values of various substituted pyridines with their gas-phase basicities is presented in Figure 1. Similar trends of attenuation of substituent effects while going from solvent to the gas phase were observed also in previous studies.<sup>7,38</sup> These results confirm the previous findings<sup>7</sup> that the basicities of neutral bases are significantly less sensitive toward structural effects than the basicities of the anionic bases.

**The nature of the phosphorus–nitrogen double bond** in (arylimino)tris(1-pyrrolidinyl)phosphoranes and (arylimino)tris(dimethylamino)phosphoranes is an important question in rationalizing the basicity data of these compounds. The chemistry of iminophosphoranes is somewhat analogous to the chemistry of phosphorus

**Scheme 1**



ylides. The phosphorus–carbon bond in the phosphorus ylides is commonly described by two canonical structures (see Scheme 1), *ylenic* **30** and *ylidic* **31**.<sup>37</sup> Modern theoretical calculations and experimental physical methods have shown that the ylidic structure has higher contribution to the phosphorus ylides. Interestingly, the nature of the phosphorus–nitrogen double bond has received far less attention. It is most commonly represented as a formal double bond, and in the case simple of alkyl and aryl iminophosphoranes this approach is supported by X-ray crystallography and electron diffraction experiments.<sup>10</sup>

When correlating the  $pK_a$  values in AN for ring-substituted (unsubstituted, 4-MeO, 4-Br, 2-Cl, 2,5-Cl<sub>2</sub>) (arylimino)tris(1-pyrrolidinyl)phosphoranes and ring-substituted 2-phenyl-1,1,3,3-tetramethylguanidines from ref 8, then the following equation is obtained:  $pK_a(\text{PhP1-pyrr}) = (-5.7 \pm 0.9) + (1.36 \pm 0.05) pK_a(\text{PhTMG})$ ;  $n = 5$ ;  $r^2 = 0.996$ ;  $s = 0.127$ . It appears that the basicities of the mentioned phosphoranes are 1.3 – 1.4 times more sensitive toward substitution in the phenyl group. The second interesting feature is that the  $pK_a$  difference (6.5  $pK_a$  units) is far higher between  $\text{MeN}=\text{P}(\text{NMe}_2)_3$  ( $pK_a = 27.55^4$ ) and **5** than between pentamethylguanidine ( $pK_a = 25.00^4$ ) and **7** (4.4  $pK_a$  units). At first these findings seem surprising because the degree of delocalization of the positive charge in the protonated iminophosphoranes is expected to be higher as a result of a larger number of NMe<sub>2</sub> fragments (3 vs 2) and the more electropositive character of phosphorus atom in phenyliminophosphoranes as compared to carbon atom in PhTMGs. If one assumes that the phosphorus–nitrogen bond is a double bond, then no appreciable delocalization of the lone electron pair from the imino nitrogen takes place into the aromatic ring in either group of compounds.

If, however, we assume in these iminophosphoranes a certain contribution of the ylidic (zwitterionic) structure (see Scheme 1) analogous to the ylidic structure in phosphorus ylides, the situation seems far more logical. The ylidic structure is isoelectronic with phenols, and therefore delocalization of the electrons on the imino nitrogen into the aromatic ring can be expected.

Thus, our basicity measurements provide evidence about some contribution of the ylidic structure in the (arylimino)tris(1-pyrrolidinyl)phosphoranes and (arylimino)tris(dimethylamino)phosphoranes.

Tang et al.<sup>5</sup> have found the polycyclic phosphazene **32** (see Scheme 2) to be a weaker base than DBU and stronger than **5** in deuterated AN. In other words, its basicity is quite similar to the basicity of **4**, although the exact  $pK_a$  is not given. They have suggested the trans-annulation in the polycyclic cage as shown in **33** to significantly enhance the stability of the protonated **32**. However, this base strengthening effect cannot be considered very large (maybe around 2  $pK_a$  units) because even substitution of three dimethylamino groups in **5** with three quite similar pyrrolidino groups already gives a base-strengthening effect of about one  $pK_a$  unit.

(34) (a) Minkin, V. I.; Bren', V. A.; Garnovskii, A. D.; Nikitina, R. I. *Zh. Geterotsikl. Soedinenii* **1972**, *4*, 552–557. (b) Zvezdina, E. A.; Zdanova, M. P.; Bren', V. A.; Dorofeenko, G. N. *Zh. Geterotsikl. Soedinenii* **1974**, *11*, 1461–1467. (c) Zvezdina, E. A.; Derbenev, V. V.; Bren', V. A.; Popova, A. N.; Dorofeenko, G. N. *Zh. Geterotsikl. Soedinenii* **1976**, *8*, 1025–1028.

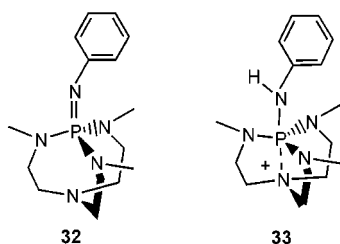
(35) (a) Pawlak, Z.; Kuna, S.; Richert, M.; Giersz, E.; Wisniewska, M.; Liwo, A.; Chmurzynski, L. *J. Chem. Thermodyn.* **1991**, *23*, 135–140. (b) Pawlak, Z.; Urbanczyk, G. *J. Mol. Struct.* **1988**, *177*, 401–406. (c) Pawlak, Z. *J. Chem. Thermodyn.* **1987**, *19*, 443–447. (d) Pawlak, Z.; Zundel, G.; Fritsch, J.; Wawrzynów, A.; Kuna, S.; Tusk, M. *Electrochim. Acta* **1984**, *29*, 391–395. (e) Pawlak, Z.; Tusk, M.; Kuna, S.; Strobusch, F.; Fox, M. *J. Chem. Soc., Faraday Trans. 1* **1984**, *80*, 1757–1768. (f) Pawlak, Z.; Wawrzynów, A.; *J. Chem. Soc., Faraday Trans. 1* **1983**, *79*, 1523–1531.

(36) Zdanov, J. A.; Bren', V. A.; Alekseeva, V. G.; Alekseev, J. E.; Fomina, V. N. *Dokl. Akad. Nauk SSSR* **1974**, *219*, 108–110.

(37) Kolodiazny, O. I. *Phosphorus Ylides*; Wiley-VCH: Weinheim, 1999.

(38) Koppel, I. A.; Koppel, J. B.; Muuga, L. I.; Pihl, V. O. *Org. React.* **1988**, *25*, 131–146.

Scheme 2



Comparison of the two sets of compounds, **4**, **5**, **7**, **32** vs. phenyl-substituted (arylimino)tris(1-pyrrolidinyl)phosphoranes, makes it clear that the latter series has a larger potential in differentiation of basicities, with  $pK_a$  values quite well predictable from analogues. This knowledge is very useful for creating new reference base series for basicity measurements in regions where good references are lacking.

### Conclusion

A self-consistent spectrophotometric basicity scale in acetonitrile including DBU, ten (arylimino)tris(1-pyrroli-

dinyl)phosphoranes, two (arylimino)tris(dimethylamino)phosphoranes, 2-phenyl-1,1,3,3-tetramethylguanidine, 1-(2-tolyl)biguanide, benzylamine, two substituted benzimidazoles, pyridine, and ten substituted pyridines has been created. All together 29 different bases were studied, and 53 independent equilibrium constant measurements were carried out, each describing the relative basicity of two bases. The scale is anchored to the formerly measured  $pK_a$  value of pyridine of 12.33. Our basicity measurements provide evidence for some contribution of the ylidic structure in the (arylimino)tris(1-pyrrolidinyl)phosphoranes and (arylimino)tris(dimethylamino)phosphoranes.

**Acknowledgment.** This work was supported by grants 4376, 3992, and 3366 from the Estonian Science Foundation. We are greatly indebted to Mr. Viljar Pihl for his assistance with various experimental aspects of this work and to Dr. Vahur Mäemets for the NMR measurements.

JO005521J