increased smoothly with time and reached a maximum at complete conversion. The same experiment was repeated several times, and the variability for each time point was less than 5%. This result indicates that MALDI, when combined with SAMs, may find wider use for kinetic analysis of interfacial reactions.

The most significant result of this work is that a commercial instrument for MALDI-TOF MS, when combined with self-assembled monolayers engineered for bioanalytical applications, is a very effective technique for characterizing biological activities at interfaces. We believe that this finding will be exploited for a range of purposes, but in particular for examining biochips. The recent development of strategies that use self-assembled monolayers for the preparation of peptide, protein, and carbohydrate arrays makes this technique immediately applicable.[14,23,24] The use of MALDI in these applications is significant because it can identify unexpected biological activities, while current methods for characterizing biochips require preliminary knowledge of the activity to be identified. Fluorescence detection of antibodies that bind to arrays, for example, will only identify activities that introduce or delete an antigen. Mass spectrometry, by contrast, will identify any change in mass at the interface—whether resulting from binding of a protein or modification by an enzyme—and hence can discover unanticipated activities. We believe that these properties, together with the widespread availability of commercial instruments, will make MALDI a popular and effective technique for applications in bioanalytical and surface chemistry.

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[1] H. Zhu, J. F. Klemic, S. Chang, P. Bertone, A. Casmayor, K. G. Klemic, D. Smith, M. Gerstein, M. A. Reed, M. Snyder, *Nat. Genet.* **2000**, *26*, 283–289.

[2] R. M. T. de Wildt, C. R. Mundy, B. D. Gorick, I. M. Tomlinson, *Nat. Biotechnol.* **2000**, *18*, 989–994.

[3] U. Reineke, R. Volkmer-Engert, J. Schneider-Mergener, *Curr. Opin. Biotechnol.* **2001**, *12*, 59–64.

[4] P. J. Hergenrother, K. M. Depew, S. L. Schreiber, *J. Am. Chem. Soc.* **2000**, *122*, 7849–7850.

[5] M. Merchant, S. R. Weinberger, *Electrophoresis* **2000**, *21*, 1164–1177.

[6] T. Natsume, H. Nakayama, T. Isobe, *Trends Biotechnol.* **2001**, *19*, S28-S33.

[7] H. Zou, Q. Zhang, Z. Guo, B. Guo, Q. Zhang, X. Chen, *Angew. Chem.* **2002**, *114*, 668–670; *Angew. Chem. Int. Ed.* **2002**, *41*, 646–648.

[8] R. L. McCarley, T. D. McCarley, *Anal. Chem.* **1997**, *69*, 130–136.

[9] J. L. Trevor, K. R. Lykke, M. J. Pellin, L. Hanley, *Langmuir* **1998**, *14*, 1664–1673.

[10] L. Hanley, O. Kornieko, E. T. Ada, E. Fuoco, J. L. Trevor, *J. Mass Spectrom.* **1999**, *34*, 705–723.

[11] K. L. Prime, G. M. Whitesides, *J. Am. Chem. Soc.* **1993**, *115*, 10714–10721.

[12] M. Mrksich, G. B. Sigal, G. M. Whitesides, *Langmuir* **1995**, *11*, 4383–4385.

[13] B. T. Houseman, M. Mrksich, *Angew. Chem.* **1999**, *111*, 876–880; *Angew. Chem. Int. Ed.* **1999**, *38*, 782–785.

[14] B. T. Houseman, J. H. Huh, S. J. Kron, M. Mrksich, *Nat. Biotechnol.* **2002**, *20*, 270–274.

[15] G. Pale-Grosdemange, E. S. Simon, K. L. Prime, G. M. Whitesides, *J. Am. Chem. Soc.* **1991**, *113*, 12–20.

[16] B. T. Houseman, E. S. Gawalt, M. Mrksich, *Langmuir*, in press.

[17] Monolayers were prepared as described previously.[13] Substrates were cut into 1 cm$^2$ chips and treated with acetonitrile containing 2,5-dihydroxybenzoic acid (10 mg mL$^{-1}$, 1 μL). The substrates were allowed to dry and then analyzed on a Voyager-DE Biospectrometry mass spectrometer operating in the delayed extraction mode with a 3-ns pulse nitrogen laser (337 nm) for desorption and ionization with an accelerating voltage of 20 kV. Ions were detected as positive ions on a time-of-flight mass detector in the reflector mode, and external standards were used for mass calibration.

[18] When reporting the ratio of alkanethiolates present in a mixed SAM, we give the ratio of alkanethiols in the solutions used for the formation of the monolayer.

[19] The majority of the SAMs in this work gave mainly sodium adducts of the molecular ions. Throughout the text we provide empirical formulas and the expected monoisotopic masses for each observed disulfide.

[20] We found that application of a matrix was necessary for the observation of molecular ions from the monolayers, but we have not optimized the formulation of the matrix for these applications.

[21] Concanavalin A is a tetramer with four identical subunits. Under acidic conditions, this noncovalent protein polymer dissociates easily. For a reference spectrum, see: M. Monatte, C. Lesieur, B. Vécsey-Semjén, J. T. Buckley, F. Pattus, F. G. van der Goot, A. Van Dorsselaer, *Int. J. Mass Spectrom. Ion Processes* **1997**, *169*/170, 179–199.

[22] *A*: integration area of peaks, L: peak for LacNAc, G: peak for GlcNAc.

[23] B. T. Houseman, M. Mrksich, *Chem. Biol.* **2002**, *9*, 443–454.

[24] C. D. Hodneland, Y. S. Lee, D. H. Min, M. Mrksich, *Proc. Natl. Acad. Sci. USA* **2002**, *99*, 5084–5052.

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# A Method for Determining the Difference in Relative Apicophilicity of Carbon-Containing Substituents of 10-P-5 Phosphoranes[**]

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Satoshi Kojima, Shin-ya Furuta,
Yohsuke Yamamoto, and Kin-ya Akiba*

Apicophilicity is the relative preference of substituents to occupy the apical positions as opposed to the equatorial positions in trigonal bipyramidal (TBP) structures and is one of the fundamental properties of pentacoordinate compounds.

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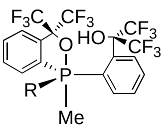
Supporting information for this article is available on the WWW under http://www.angewandte.org or from the author.

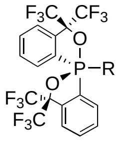
Especially, the implication that pentacoordinate intermediates play important roles in the reaction of phosphoryl groups in biological systems has given rise to theoretical and experimental investigations, which culminated in several apicophilicity scales for a variety of heteroatom substituents.[1,2] Experimental scales have mostly been built upon the relative activation energy of pseudorotation (a kinetic feature) of a series of phosphoranes that differ only in the substituent in question, by using techniques such as dynamic NMR spectroscopy in solution. According to the definition, however, the ideal apicophilicity scale should be based on the relative thermodynamic stability of two configurationally isomeric phosphoranes that differ only by interchange of one apical and one equatorial substituent, which are directly attached to the phosphorus center. Comparisons of stability between such isomers should especially be effective for the determination of relative apicophilicity among substituents of similar electronegativities, which would otherwise be extremely difficult to establish. Although some publications have appeared on the coexistence of such positional isomers in equilibrated mixtures,[3,4] no experimental investigation on relative apicophilicity in a thermodynamic sense has been reported except for that on $CF_3$ and F, which are of very similar apicophilicities.[4] In addition, although reactions of biological systems occur in aqueous media and it is thus essential to examine the effect of solvents on apicophilicity, no such effects have been observed to date, probably because of a lack of suitable systems to examine.

We recently prepared a novel family of phosphoranes **2** with an "anti-apicophilic" *O-cis* array of substituents containing carbon and oxygen atoms directly attached to the phosphorus center (equatorial oxygen–apical carbon atoms).[5] In an investigation of the reactivity of these unique phosphoranes, **1a** was a reaction product with MeLi.[6] This compound shows two distinct signals for the two methyl groups in the $^1$H NMR spectrum, which suggested the possibility to freeze pseudorotation on the NMR spectroscopic timescale for phosphoranes bearing two different monodentate substituents directly connected to the phosphorus center through carbon atoms, and thus simultaneously show the presence of two isomeric phosphoranes which differ only in the position of these two substituents. To this end, several such compounds were prepared; these did show the coexistence of pairs of pseudorotamers. Here we report on a new method for determining the relative apicophilicity of several substituents on the phosphorus center that are directly attached by a carbon atom, based on the equilibrium ratio of these pairs of pseudorotamers in solution, that is, based on relative thermodynamic stability. In the process, we also found a distinct solvent effect on relative apicophilicity, and a novel phenomenon in which two different pseudorotamers (**1hA** and **1hB**) cocrystallize in the same single crystal by adjustment of the two substituents, which are carbon-containing groups (benzyl, Me), and of the recrystallization solvent ($CH_3CN$).



**1a-i**

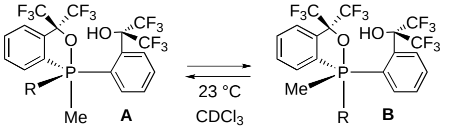
**1a**: R = Me
**1b**: R = Et
**1c**: R = *n*Pr
**1d**: R = *n*Bu
**1e**: R = $CH_2OMe$
**1f**: R = Ph
**1g**: R = $CH_2C_6H_4$(*p*-Me)
**1h**: R = $CH_2Ph$
**1i**: R = $CH_2C_6H_4$(*p*-F)



**2**

The $^{31}$P NMR spectrum of **1a** in $CDCl_3$ showed a singlet ($\delta = -34.8$ ppm), and two resonance signals arising from methyl groups ($\delta = 2.57$ (d, $^2J_{PCH} = 13.7$ Hz, 3H), 1.46 ppm (d, $^2J_{PCH} = 5.9$ Hz, 3H)) were observed in the $^1$H NMR spectrum at 23 °C. These observations suggested that the two-step Berry pseudorotation process,[7] which interchanges an apical and an equatorial substituent, was slowed down and the stereochemistry was fixed on the NMR spectroscopic timescale (Table 1). There have been ample demonstrations that pseudorotation is too fast to enable the determination of such equilibrium ratios in ordinary monocyclic compounds.[1a,b,2,8] However, the present system shows a unique and successful example, in which an intramolecular hydrogen bond between the hydroxy group of the monodentate aryl group and the apical oxygen atom of the five-membered ring could stabilize the stereochemistry of the 10-P-5 phosphoranes **1**.

Table 1. Substituent effect on the equilibrium ratios ($CDCl_3$) in **1b**–**1i**, and chemical shifts ($CDCl_3$, $\delta$), and coupling constants ($^2J_{PCH}$) of the resonance signals for the methyl groups in the $^1$H NMR spectra of **1a**–**1i**.



| | R | Equilibrium ratio **A**:**B**[a] | $\Delta G°_{A\text{-}B}$ [kcal mol$^{-1}$] | $\sigma_I$ | $E_S$ | Chemical shifts $\delta$ [ppm] **A** | **B** | Coupling constants $^2J_{PCH}$ [Hz] **A** | **B** |
|---|---|---|---|---|---|---|---|---|---|
| **1a** | Me | | | −0.01 | 0.00 | 1.46 | 2.57 | 5.9 | 13.7 |
| **1b** | Et | 3.8:1 | −0.79 | −0.01 | −0.07 | 1.47 | 2.59 | 5.9 | 13.3 |
| **1c** | *n*Pr | 5.0:1 | −0.95 | −0.01 | −0.36 | 1.48 | 2.60 | 6.0 | 13.3 |
| **1d** | *n*Bu | 5.0:1 | −0.95 | −0.01 | −0.39 | 1.48 | 2.60 | 5.9 | 13.7 |
| **1e** | $CH_2OMe$ | 1:10 | 1.35 | 0.11 | −0.19 | 1.60 | 2.64 | 7.0 | 14.5 |
| **1f** | Ph | < 2: > 98 | > 2.7 | 0.12 | | – | 2.75 | – | 13.7 |
| **1g** | $CH_2C_6H_4$(*p*-Me) | 3.7:1 | −0.77 | | | 1.17 | 2.63 | 6.3 | 13.4 |
| **1h** | $CH_2Ph$ | 3.0:1 | −0.65 | 0.03 | −0.38 | 1.17 | 2.64 | 6.4 | 13.7 |
| **1i** | $CH_2C_6H_4$(*p*-F) | 2.4:1 | −0.52 | | | 1.18 | 2.63 | 8.3 | 13.4 |

[a] **A**:**B** was determined by the integral values taken from the $^1$H or $^{19}$F NMR spectra.

The phosphorane **1b** was prepared by a similar method.[9] The $^{31}$P NMR spectrum of **1b** showed two singlets ($\delta = -21.9$ (major) and $-25.3$ ppm (minor); ratio: 3.8:1 in $CDCl_3$ at 23 °C) and two sets of signals arising from methyl and ethyl groups were observed in the $^{1}$H and $^{13}$C NMR spectra. For the major component, the coupling constants for the coupling of the methyl group protons and carbon atom to the phophorus center ($\delta = 1.47$ ($^{2}J_{PCH} = 5.8$ Hz), and 21.3 ppm ($^{1}J_{PC} = 27.1$ Hz)) were much smaller than the corresponding coupling constants of the minor component ($\delta = 2.59$ ($^{2}J_{PCH} = 13.3$ Hz) and 24.5 ppm ($^{1}J_{PC} = 97.9$ Hz)). Because coupling constants between an atom of an equatorial group and the central atom are generally larger than those between an atom of an apical group and the central atom,[1,10] the major component was assigned the structure **1bA** (apical methyl and equatorial ethyl groups), which coincides with its X-ray crystal structure (Figure 1). Likewise, the minor component was assigned to be the pseudorotamer **1bB** (apical ethyl and equatorial methyl groups; Table 1). The X-ray analysis showed that the geometry about the phosphorus atom in **1bA** is a slightly distorted TBP with three carbon atoms (two *ipso* carbon atoms of the two Martin ligands,[1i] and the α carbon atom of the ethyl group in **1bA**) are at the equatorial sites of the TBP. As expected, the hydroxy proton on the oxygen atom O(2) of the monodentate ligand is hydrogen-bonded with the apical oxygen atom O(1) of the Martin ligand, which holds the relatively electronegative aryl group in the equatorial position.

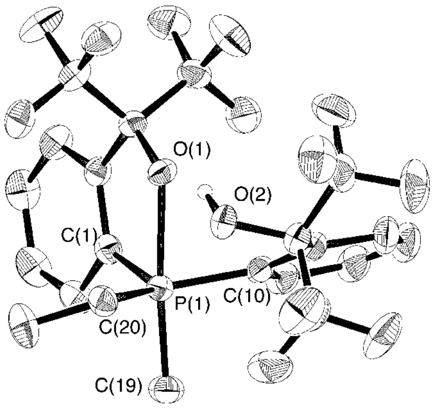


Figure 1. ORTEP drawing of **1bA** (thermal ellipsoids set at 30%).

Apicophilicity is governed by electronic and steric effects. Electronically, the more electronegative substituent usually prefers the apical position, whereas the more bulky substituent usually prefers the equatorial position. In the major component **1bA** the methyl group occupies the apical position, which supports the expectation that the apicophilicity of a methyl group is higher than that of an ethyl group, based on steric grounds, because the electronic effect is the same for both methyl and ethyl groups ($\sigma_I = -0.01$ for both, see Table 1).[1] To confirm that the assignments of stereochemistry are correct and that the observed ratio is based on thermodynamics, the crystal used for X-ray analysis was dissolved in toluene at −40 °C. At this temperature, only one set of signals (consistent with the major isomer **1bA**) was observed in the $^{31}$P, $^{1}$H, and $^{13}$C NMR spectra. After the solution was warmed to −20 °C, another set of signals (corresponding to **1bB**) appeared gradually; equilibration was complete after 2 h at −20 °C. The rates of equilibration were calculated to be $3.22 \pm 0.12 \times 10^{-5}$ s$^{-1}$ (**1bA→1bB**) and $1.40 \pm 0.05 \times 10^{-4}$ s$^{-1}$ (**1bA←1bB**). Based on these values, the equilibration should be complete at 23 °C within 0.1 s.

Other derivatives (**1c**–**1i**) were also prepared, the $^{1}$H, $^{13}$C, and $^{31}$P NMR spectroscopic data of which were very similar to those of **1b** (Table 1; see Supporting Information for $^{13}$C and $^{31}$P NMR spectroscopic data).[9] Therefore, the structures of the pseudorotamers in **1c**–**1i** were assigned similarly. The equilibrium ratios of **1c**–**1i** in $CDCl_3$ are summarized in Table 1 together with the values of their Hammett inductive constants ($\sigma_I$),[11] and the steric substituent constants ($E_s$).[12] A comparison among the series of phosphoranes bearing two different alkyl substituents (**1b**–**1d**) shows that steric factors play important roles in apicophilicity, because the $\sigma_I$ constants are the same for the methyl, ethyl, *n*-propyl, and *n*-butyl groups. For **1f**, which has a phenyl group, only one singlet was observed ($\delta = -22.5$ ppm) in the $^{31}$P NMR spectrum ($CDCl_3$) and one resonance signal of a methyl group ($\delta = 2.75$ ppm (d, $^{2}J_{PCH} = 13.7$ Hz, 3H)) was observed in the $^{1}$H NMR spectrum, which indicate that the isomer **1fB** (apical phenyl and equatorial methyl groups) is exclusive in solution. The assignment was consistent with the X-ray analysis of **1f**, which does have the proposed structure **1fB** (see Supporting Information). This result shows that the apicophilicity of a phenyl group is considerably higher than that of a methyl group. The reason is probably because the phenyl group ($\sigma_I = 0.12$ in Table 1) is more electronegative than the methyl group ($\sigma_I = -0.01$).[1] Previous examinations of the relative apicophilicity between methyl and phenyl groups have produced conflicting results as, for example, Trippett and co-workers concluded that the methyl group was more apicophilic than the phenyl group,[13] whereas Holmes reported the opposite.[1b] Our results are consistent with those of Holmes.

The examination of intermediary cases would be interesting, that is, compounds in which one of the hydrogen atoms in the methyl group of **1a** is replaced with an electronegative group. Here, steric hindrance and electronegativity of the group are expected to work in opposite directions. Thus, for the highly electronegative and relatively small methoxymethyl group, a higher composition of the isomer of type **B** is expected than that in **1b** or **1c**. For the pair of isomers bearing the methoxymethyl group **1e**, the major isomer in the equilibrium is **1eB**, which shows that the inductive electronic effect overrides the steric effect. For **1h**, the major component was assigned the structure **1hA** (apical methyl and equatorial benzyl) and the minor component **1hB** (apical benzyl and equatorial methyl). The effect of the *para*-$CH_3$ and F substituents (**1g** and **1i**) on the equilibrium ratio resulted in a shift of the equilibrium ratio towards isomer **B** with the more electronegative substituent (**1g** < **1h** < **1i**), which indicates that the remote electronic effect through a benzene ring can also play a significant role. Therefore, in these cases, there is a counterbalance between the two factors, with the steric factor slightly dominating the electronic factor. Thus, the apicophilicity order of ligands that are directly attached to the

Table 2. Solvent effect on the equilibrium ratios in **1b**–**1i** together with solvent parameters.

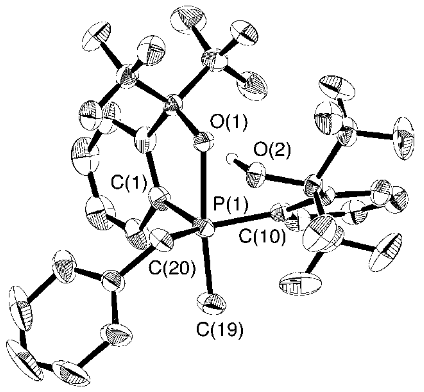
| | | $CDCl_3$ | $C_6D_6$ | [$d_8$]THF | [$d_6$]Acetone | $CD_3CN$ |
|---|---|---|---|---|---|---|
| | $\varepsilon$[a] | 4.89 | 2.40 | 7.47 | 21.36 | 36.00 |
| | $\mu$ [$\times 10^{-30}$ Cm][a] | 3.8 | 0 | 5.8 | 9.0 | 11.8 |
| | $E_T^N$[a] | 0.259 | 0.111 | 0.207 | 0.355 | 0.460 |
| | R | **A**:**B**[b] | **A**:**B**[b] | **A**:**B**[b] | **A**:**B**[b] | **A**:**B**[b] |
| **1b** | Et | 3.8:1 | 3.8:1 | 3.3:1 | 2.8:1 | 2.8:1 |
| **1c** | *n*Pr | 5.0:1 | 4.5:1 | 3.7:1 | 3.2:1 | 3.8:1 |
| **1d** | *n*Bu | 5.0:1 | 4.6:1 | 3.5:1 | 3.2:1 | 4.0:1 |
| **1e** | $CH_2OMe$ | 1:10 | 1:9.8 | 1:15 | 1:11 | 1:9.7 |
| **1f** | Ph | $<2:>98$ | $<2:>98$ | $<2:>98$ | $<2:>98$ | $<2:>98$ |
| **1g** | $CH_2C_6H_4$(*p*-Me) | 3.7:1 | 3.1:1 | 2.0:1 | 1.6:1 | 1.1:1 |
| **1h** | $CH_2Ph$ | 3.0:1 | 2.3:1 | 1.3:1 | 1:1 | 1:1.2 |
| **1i** | $CH_2C_6H_4$(*p*-F) | 2.4:1 | 2.2:1 | 1.1:1 | 1:1.5 | 1:1.7 |

[a] Values of undeuterated solvents. [b] **A**:**B** was determined by the integral values in the $^1$H or $^{19}$F NMR spectra.

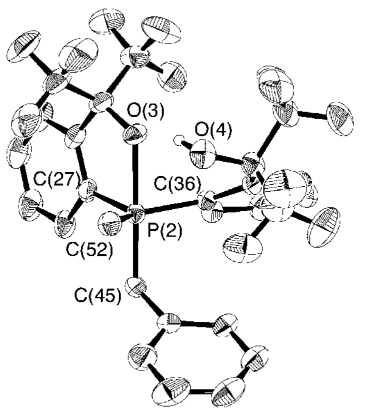
phosphorus by a carbon atom in $CDCl_3$ is as follows: Ph $\gg$ $CH_2OMe$ $\gg$ Me $>$ $CH_2C_6H_4$(*p*-F) $>$ $CH_2Ph$ $>$ $CH_2C_6H_4$(*p*-Me) $\approx$ Et $>$ *n*Pr $\approx$ *n*Bu.

When the solvent was changed from $CDCl_3$ to other solvents a distinct difference was observed, especially for the benzyl-substituted compounds (**1g**–**1i**). The equilibrium ratios in these solvents are shown in Table 2 together with solvent parameters ($\varepsilon$,[14] $\mu$,[14] and $E_T^N$[14]). As a general trend, pseudorotamer **A** (**1gA**–**1iA**) was preferred in less polar solvents, and the ratios depended on the polarity of solvents. It should be noted that in $CD_3CN$ the order of apicophilicity of the benzyl and methyl groups is reversed to 1:1.2 for **1h** and 1:1.7 for **1i**. This phenomenon suggests that the contribution of the electronic factor overcomes that of the steric factor in more polar solvents, especially in $CD_3CN$. Thus, in $CD_3CN$ the apicophilicity order of ligands with carbon atoms directly attached to the carbon center is changed to Ph $\gg$ $CH_2OMe$ $\gg$ $CH_2C_6H_4$(*p*-F) $>$ $CH_2Ph$ $>$ Me $>$ $CH_2C_6H_4$(*p*-Me) $>$ Et $>$ *n*Pr $>$ *n*Bu.

Interestingly, the X-ray structures of **1g** and **1i**, which were crystallized from $CH_3CN$, coincided with the major pseudorotamer in $CD_3CN$, that is, **1gA** and **1iB**, respectively, although the isomer compositions were not far from 1:1. Similar precedence was recently seen in the study of spirophosphoranes bearing an eight-membered ring.[3e] The X-ray analysis of **1h** was more surprising, as it showed the presence of two pseudorotamers in the same crystal, that is, **1hA** and **1hB**. The ORTEP drawings of the two independent molecules are shown in Figure 2.[15] To our knowledge, this is the first example of the cocrystallization of two different pentacoordinate pseudorotamers in the same single crystal. Further investigations on analogous pseudorotamers with two carbon-atom-linked substituents of similar apicophilicity are in progress.



1st molecule: **1hA**



2nd molecule: **1hB**

Figure 2. ORTEP drawing of **1h** (thermal ellipsoids set at 30%).

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[1] a) K.-y. Akiba, *Chemistry of Hypervalent Compounds*, Wiley-VCH, Weinheim, **1999**; b) R. R. Holmes, *Pentacoordinated Phosphorus—Structure and Spectroscopy; ACS Monograph 175, 176, Vols. I, II*, American Chemical Society, Washington, DC, **1980**; c) S. Trippett, *Phosphorus Sulfur* **1976**, *1*, 89–98; d) R. Burgada, R. Setton in *The Chemistry of Organophosphorus Compounds* (Ed.: F. R. Hartley), Wiley-Interscience, Chichester, **1994**, pp. 185–272; e) R. S. McDowell, A. Streitwieser, Jr., *J. Am. Chem. Soc.* **1985**, *107*, 5849–5855; f) P. Wang, Y. Zhang, R. Glaser, A. E. Reed, P. v. R. Schleyer, A. Streitwieser, *J. Am. Chem. Soc.* **1991**, *113*, 55–64; g) G. R. J. Thatcher, A. S. Campbell, *J. Org. Chem.* **1993**, *58*, 2272–2281; h) B. D. Wladkowski, M. Krauss, W. J. Stevens, *J. Phys. Chem.* **1995**, *99*, 4490–4500; i) J. C. Martin, *Science* **1983**, *221*, 509–514; j) E. L. Muetterties, W. Mahler, R. Schmutzler, *Inorg. Chem.* **1963**, *2*, 613–618.

[2] a) M. Nakamoto, S. Kojima, S. Matsukawa, Y. Yamamoto, K.-y. Akiba, *J. Organomet. Chem.* **2002**, *643–644*, 441–452; b) S. Kojima, M. Nakamoto, K. Kajiyama, K.-y. Akiba, *Tetrahedron Lett.* **1995**, *36*, 2261–2264; c) S. Kojima, M. Nakamoto, K. Yamazaki, K.-y. Akiba, *Tetrahedron Lett.* **1997**, *38*, 4107–4110.

[3] a) T. Kawashima, T. Soda, K. Kato, R. Okazaki, *Phosphorus Sulfur Silicon* **1996**, *109–110*, 489–492; b) T. Kawashima, T. Soda, R. Okazaki, *Angew. Chem.* **1996**, *108*, 1206–1208; *Angew. Chem. Int. Ed. Engl.* **1996**, *35*, 1096–1098; c) N. V. Timosheva, T. K. Prakasha, A. Chandrasekaran, R. O. Day, R. R. Holmes, *Inorg. Chem.* **1995**, *34*, 4525–4526; d) N. V. Timosheva, A. Chandrasekaran, T. K. Prakasha, R. O. Day, R. R. Holmes, *Inorg. Chem.* **1996**, *35*, 6552–6560; e) S. Kumaraswamy, C. Muthiah, K. C. Kumara Swamy, *J. Am. Chem. Soc.* **2000**, *122*, 964–965.

[4] O. Lösking, H. Willner, H. Oberhammer, J. Grobe, D. L. Van, *Inorg. Chem.* **1992**, *31*, 3423–3427.

[5] a) K. Kajiyama, M. Yoshimune, M. Nakamoto, S. Matsukawa, S. Kojima, K.-y. Akiba, *Org. Lett.* **2001**, *3*, 1873–1875; b) S. Kojima, K. Kajiyama, M. Nakamoto, K.-y. Akiba, *J. Am. Chem. Soc.* **1996**, *118*, 12866–12867; c) K. Kajiyama, S. Kojima, K.-y. Akiba, *Tetrahedron Lett.* **1996**, *37*, 8409–8412.

[6] S. Matsukawa, S. Kojima, K. Kajiyama, Y. Yamamoto, K.-y. Akiba, S. Re, S. Nagase, *J. Am. Chem. Soc.* **2002**, *124*, in press..

[7] R. S. Berry, *J. Chem. Phys.* **1960**, *32*, 933–938.

$$\mathbf{1bA}\xrightarrow{\Psi_{\mathrm{Et}}}\xrightarrow{\Psi_{\mathrm{Me}}}\mathbf{1bB}$$

[8] R. M. Moriarty, J. Hiratake, K. Liu, A. Wendler, A. K. Awasthi, R. Gilardi, *J. Am. Chem. Soc.* **1991**, *113*, 9374–9375.

[9] Spectroscopic data and ORTEP drawings are in the Supporting Information. Synthesis and complete characterization of the compounds will be reported in due course.

[10] S. Berger, S. Braun, H.-O. Kalinowski, *NMR Spectroscopy of the Non-Metallic Elements*, Wiley, Chichester, **1997**, p. 900.

[11] M. Charton, *Prog. Phys. Org. Chem.* **1981**, *13*, 119–251.

[12] R. W. Taft, Jr., *Steric Effects in Organic Chemistry* (Ed.: M. S. Newman), Wiley, New York, **1956**, p. 598.

[13] S. A. Bone, S. Trippett, P. J. Whittle, *J. Chem. Soc. Perkin Trans. 1* **1977**, 437–438.

[14] C. Reichardt, *Solvents and Solvent Effects in Organic Chemistry*, VCH, Weinheim, **1988**, pp. 407–411.

[15] CCDC-192716 (**1b**) and CCDC-153789 (**1h**) contain the supplementary crystallographic data for this paper. These data can be obtained free of charge via www.ccdc.cam.ac.uk/conts/retrieving.html (or from the Cambridge Crystallographic Data Centre, 12 Union Road, Cambridge CB21EZ, UK; fax: (+44)1223-336-033; or deposit @ccdc.cam.ac.uk). Crystals suitable for X-ray structure determination were mounted on a Mac Science DIP2030 imaging plate equipped with graphite-monochromated $\mathrm{Mo}_{\mathrm{K}\alpha}$ radiation ($\lambda = 0.71073$ Å). Unit cell parameters were determined by autoindexing several images in each data set separately with program DENZO.[16] For each data set, rotation images were collected in 3° increments with a total rotation of 180° about $\phi$. Data were processed by using SCALEPACK.[16] The structure was solved using the teXsan (Rigaku) system and refined by the full-matrix least-squares method. Crystal data for **1b**: monoclinic system, space group $P2_1/n$ (no. 14), $a = 10.4300(2)$, $b = 18.0140(4)$, $c = 12.4740(3)$ Å, $\beta = 102.795(1)°$, $V = 2285.49(9)$ Å$^3$, $Z = 4$, $\rho_{\mathrm{calc}} = 1.628$ g cm$^{-3}$. $R = 0.0650$ ($Rw = 0.1453$) for 4749 observed reflections (325 parameters) with $I > 3\sigma(I)$. Goodness of fit = 1.362. Selected bond lengths [Å]: P(1)-O(1) 2.120(2), P(1)-C(1) 1.824(3), P(1)-C(10) 1.849(3), P(1)-C(19) 1.855(3), P(1)-C(20) 1.838(3). **1h**: triclinic system, space group $P$-1 (no. 2), $a = 11.7550(4)$, $b = 12.5610(8)$, $c = 18.904(1)$ Å, $\alpha = 93.532(2)$, $\beta = 102.047(3)$, $\gamma = 100.279(4)°$, $V = 2671.8(2)$ Å$^3$, $Z = 4$, $\rho_{\mathrm{calc}} = 1.547$ g cm$^{-3}$. $R = 0.0658$ ($Rw = 0.1320$) for 7190 observed reflections (740 parameters) with $I > 3\sigma(I)$. Goodness of fit = 1.767. Selected bond lengths [Å], **1hA**: P(1)-O(1) 2.078(3), P(1)-C(1) 1.809(5), P(1)-C(10) 1.850(4), P(1)-C(19) 1.853(5), P(1)-C(20) 1.865(4); **1hB**: P(2)-O(3) 2.043(3), P(2)-C(27) 1.844(5), P(2)-C(36) 1.858(4), P(2)-C(45) 1.892(5), P(2)-C(52) 1.819(5).

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# Preferential Location of Ge Atoms in Polymorph C of Beta Zeolite (ITQ-17) and Their Structure-Directing Effect: A Computational, XRD, and NMR Spectroscopic Study[**]

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Zeolites are crystalline aluminosilicates with a regular array of microporous systems which are responsible for the outstanding properties of these materials in adsorption, ion exchange, and catalysis.[1–3] Since most of these properties strongly depend on pore dimensions and topology, there is an incentive to develop tailor-made syntheses of zeolites. Although improvements in the understanding of zeolite synthesis have been made through the rational design of organic structure-directing agents (SDAs),[4] the predictable synthesis of the desired structures is far from being achieved, this is because of the large number of parameters that influence the reactions.

We recently showed that the rate of nucleation of zeolite ITQ-7, a zeolite containing double four-member rings (D4Rs), is strongly accelerated when Ge atoms are introduced into the framework.[5] Furthermore, by means of $^{19}$F and $^{29}$Si MAS NMR (MAS = magic-angle spinning) spectroscopy we indirectly postulated that the Ge atoms were preferentially occupying framework positions at the D4R units.[6] These observations made us think that the introduction of Ge atoms could direct the synthesis of zeolites towards structures containing D4Rs as secondary building units (SBUs), which are rare.[7] Our first attempt was directed to the synthesis of the previously elusive pure polymorph C of Beta zeolite, which contains D4Rs (with the International Zeolite Associ-

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