# $^{1}H$, $^{19}F$, and $^{31}P$ PGSE NMR Diffusion Studies on Chiral Organic Salts: Ion Pairing and the Dependence of a Diffusion Value on Diastereomeric Structure

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**Abstract:** $^{1}H$, $^{19}F$ and $^{31}P$ pulsed field gradient spin-echo (PGSE) diffusion studies on chiral organic salts that contain hexacoordinate phosphate anions, namely tris(-tetrachlorobenzenediolato)phosphate(v) (TRISPHAT) and bis(tetrachlorobenzenediolato)mono([1,1′]binaphthalenyl-2,2′diolato)-phosphate(v) (BINPHAT), are reported. The first example of the dependence of a diffusion value on diastereomeric structure is presented. Marked solvent and concentration effects on the diffusion constants ($D$) of these salts are noted and the question of ion pairing is discussed.

**Keywords:** chiral salts · concentration effects · diffusion · ion pairs · NMR spectroscopy

## Introduction

Interactions between anions and transition metal cations can play an important role in the chemistry of the resulting salts.[1] The two charged species may interact through complexation of the anion to the metal, by ion pairing or, in special cases, through hydrogen bonding. Indeed, the nature of an anion associated with a cation can dramatically accelerate a reaction, improve its selectivity or even change its course.[2]

We have recently become interested in the use of multinuclear pulsed field gradient spin-echo (PGSE) NMR diffusion methods to probe cation/anion interactions.[3] In contrast to conductivity experiments, these studies on the translation of the ions in solution offer a more direct view of interionic interactions. One can often measure the diffusion constants ($D$) separately for the cation and anion and thus determine whether or not they interact. A relatively large number of salts currently in use in homogeneous catalysis and/or organic synthesis possess anions such as $PF_6^-$, $BF_4^-$, $CF_3SO_3^-$ or $BArF^-$.[2a,c–e,g] For these, $^{19}F$ PGSE measurements represent an important complement to $^{1}H$ PGSE NMR methods.[3,4] For some molecules, it is advantageous to use the $^{31}P$ spins as a source of diffusion data and we have previously shown this approach to be quite reliable.[5]

When a larger cation forms either a strong ion pair with, or hydrogen bonds to, a smaller anion, the $D$ value for the latter is markedly reduced. Cation/anion interactions can therefore be explored in a more direct fashion. In selected cases, with the help of $^{1}H$–$^{19}F$-HOESY data, one can also recognise *where* the two charged species interact.[6] Interestingly, the anion often approaches the cation in a rather specific way.[3a,c,6]

Our earlier PGSE studies revealed marked solvent and concentration effects on $D$ values in selected transition-metal salts.[3] As expected, there are solvents in which the cation/anion interaction is minimal (e.g., methanol) and others (e.g., dichloromethane) in which there is a significant amount of ion pairing.[3,5,6a,d] Furthermore, if low-temperature diffusion studies are required, convection problems might need to be overcome if reliable $D$ values are to be determined.[7] Details of some of these problems have been described.[5,7]

Although much has been written on chiral cations in enantioselective homogeneous catalysis,[8] the properties of chiral anions have been somewhat neglected.[9] Short-range discriminating interactions can occur within tightly associated diastereomeric ion pairs, with a resulting high level of asymmetric recognition (resolution) and/or induction (Pfeiffer effect).[9a,d,e,10] Recently, one of us has shown that

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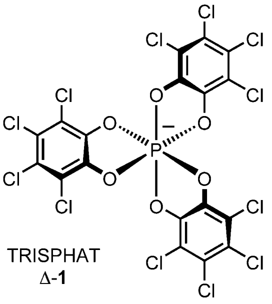
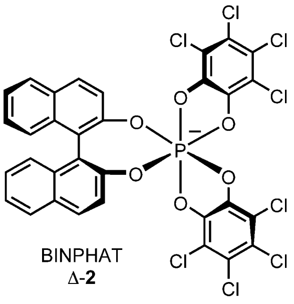
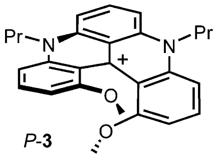
the novel chiral hexacoordinate phosphate anions tris(tetrachlorobenzenediolato)phosphate(v), (TRISPHAT, **1**),[11] and bis(tetrachlorobenzenediolato)mono([1,1′]binaphthalenyl-2,2′-diolato)-phosphate(v), (BINPHAT, **2**),[12] function as efficient NMR chiral-shift, resolving and asymmetry-inducing reagents.[13–15] Specifically, the $D_3$-symmetric TRISPHAT (as either the Δ or Λ enantiomer) has been shown to be an excellent chiral-shift reagent for a variety of chiral cationic species.[14] Asymmetric induction has been noted,[15e,g,l] with maximum observed diastereomeric excesses of about 96%.[14l,p] Interestingly, for organic cations, the $C_2$-symmetric BINPHAT is often superior to TRISPHAT with respect to both chemical shift differentation and asymmetric induction.[12,15]

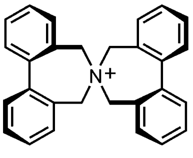

TRISPHAT
Δ-**1**


BINPHAT
Δ-**2**


*P*-**3**

Steric repulsions in the dimethoxyquinacridinium cation **3** prevent the system from being planar.[16] The molecule adopts a twisted helical conformation typical of helicene derivatives, with the possiblity of left- or right-handed chiral structures.[16] Herse et al. have shown that a salt of racemic **3** with (Δ,*S*)-BINPHAT, [**3**][Δ-**2**], exists as a 1:1 mixture of diastereomers that can be distinguished by $^1$H NMR spectroscopy. These diastereomers have been separated, and cation **3** has been shown to be configurationally stable at room temperature, unlike most [4](hetero)helicenes.[17]

Recently, chiral quaternary ammonium cations have been the subject of much attention, due to the potential of these derivatives to serve as efficient chiral-phase-transfer catalysts.[18] Cation **4** in connection with TRISPHAT or BINPHAT forms pairs of diastereomers, for example, [(*R*,*R*)-**4**][Δ-**2**] and [(*S*,*S*)-**4**][Δ-**2**], which are readily distinguished at 233 K in both dichloromethane and chloroform.[15e] Asymmetric induction from the anion onto the cation is observed for [**4**][Δ-**2**], and not for [**4**][Δ-**1**]. Circular dichroism studies reveal that the homochiral diastereomer [(*R*,*R*)-**4**][Δ-**2**] is favoured.[15e]


(*R*,*R*)-**4**

The salts of ions **1**–**4** appear to be ideal candidates for PGSE NMR studies within the context of chiral cation/anion recognition. We show here that the measured *D* values can reflect the different stabilities of the diastereomers, and that there are marked solvent and concentration effects for these salts.

## Results and Disscusion

**Concentration Effects**: Table 1 gives the *D* values for the carbocation salts [**3**][Δ-**1**], [**3**][Δ-**2**] and [**3**][$PF_6$] at different concentrations and in four different solvents (chloroform, dichloromethane, acetone and methanol). Table 2 shows the results for the ammonium salts [**4**][Δ-**1**], [**4**][Δ-**2**] and [**4**][$PF_6$] in the same solvents. The vacancies in both tables are primarily due to solubility problems or to the relatively low sensitivity of $^{31}$P in PGSE methods.

The observed concentration dependence of *D* in Table 1 over the range 1–10 mM can be significant, for example, 14–16% for the BINPHAT salt [**3**][Δ-**2**] in $CDCl_3$ and less, 7–10%, for the same salt in $CD_2Cl_2$.[19] Interestingly, in $CD_2Cl_2$, the variation is smaller for cation **3** in the TRISPHAT analogue [**3**][Δ-**1**] and in the hexafluorophosphate salt [**3**][$PF_6$] (5% and 4% respectively). The change of approximately 15% is larger than those previously noted for transition-metal complexes.[3b,c] These new data are relevant since, in the determination of molecular volumes from *D* values, a change in *D* of the order of 20–25% is usually interpreted as an effective doubling of the molecular volume.[3a,b] Consequently, the concentration dependence of the *D* values is important if errors in determining molecular sizes are to be avoided.

**Solvent effects**: To facilitate comparisons between the results in different solvents, Tables 1 and 2 show *D* values and the derived hydrodynamic radii, $r_H$. These radii are obtained from the Stokes-Einstein equation [Eq. (1)] in which *k* is the Boltzmann constant, *T* is the absolute temperature and $\eta$ is the viscosity:[20]

$$D = \frac{kT}{6\pi\eta r_H} \quad (1)$$

This equation takes into account the different viscosities of the solvents.[21] Clearly, the $r_H$ values for the more concentrated samples are large compared with the 1 mM samples, due to the concentration dependence.

In previous PGSE studies[3b,f] we reported a solvent dependence of the *D* values for the complexes **5**, **6** and the class **7**. In $CD_2Cl_2$, the *D* values (and consequently, $r_H$ values) for the $PF_6^-$ and $CF_3SO_3^-$ ions in these salts suggest that these anions move much faster than their respective cations. In $CDCl_3$ the data suggest tight ion pairs, that is, the

Table 1. $D$ [$\times 10^{10}$ m$^2$s$^{-1}$] and $r_H$ [Å][a,b] values for [**3**][Δ-**1**], [**3**][Δ-**2**] and [**3**][PF$_6$].

| | | | $D$ | $r_H$ | $D$ | $r_H$ | $D$ | $r_H$ | $D$ | $r_H$ |
|---|---|---|---|---|---|---|---|---|---|---|
| Salt | Concn [mM] | Fragment[c] | CDCl$_3$ | | CD$_2$Cl$_2$ | | acetone[D$_6$][d] | | MeOD[e] | |
| [**3**][Δ-**1**] | 10 | cation | 5.05 | 8.1 | 8.71 | 6.1 | 11.8 | 6.1 | | |
| | | anion ($^{31}$P) | 5.21 | 7.9 | 8.29 | 6.4 | 11.4 | 6.3 | | |
| | 5 | cation | 5.41[f,g] | 7.7 | 8.60[f,h] | 6.2 | | | | |
| | | anion[m] | | | | | | | | |
| | 1 | cation | 5.64 | 7.3 | 9.00 | 5.9 | 12.4 | 5.8 | 7.74 | 5.3 |
| | | anion[m] | | | | | | | | |
| [**3**][Δ-**2**] | 10 | cation | 4.67[f,i] | 8.9 | 8.08 | 6.5 | 11.8 | 6.1 | | |
| | | anion[n] | 4.66 | 8.9 | 7.10 | 7.5 | 10.5 | 6.8 | | |
| | 5 | cation | 4.91[f,j] | 8.5 | 8.11[f,k] | 6.6 | | | | |
| | | anion | 4.92 | 8.4 | 7.17 | 7.5 | | | | |
| | 1 | cation | 5.40[f,l] | 7.7 | 8.88 | 5.9 | 12.5 | 5.7 | 7.83 | 5.2 |
| | | anion | 5.33 | 7.8 | 7.61 | 6.9 | 11.0 | 6.5 | 5.88 | 7.0 |
| [**3**][PF$_6$] | 10 | cation | | | 9.70 | 5.4 | | | | |
| | | anion ($^{19}$F) | | | 13.5 | 3.9 | | | | |
| | 5 | cation | | | 9.70 | 5.4 | 12.6[o] | 5.7 | | |
| | | anion ($^{19}$F) | | | 13.9 | 3.8 | 25.8[o] | 2.8 | | |
| | 1 | cation | | | 10.0 | 5.3 | 12.8 | 5.6 | 7.97 | 5.2 |
| | | anion ($^{19}$F) | | | 14.8 | 3.6 | 26.7 | 2.7 | 15.2 | 2.7 |

[a] We propose a standard deviation of $\pm 0.06 \times 10^{-10}$ m$^2$s$^{-1}$ for $D$ values and ±0.1 Å for $r_H$ values. [b] For the calculation of $r_H$, the viscosity of the non-deuterated solvent at the temperature of the measurements (299 or 300 K) was used.[18] At 299 K these values are $0.534 \times 10^{-3}$, $0.414 \times 10^{-3}$, $0.306 \times 10^{-3}$ and $0.544 \times 10^{-3}$ Kg s$^{-1}$m$^{-1}$ for CHCl$_3$, CH$_2$Cl$_2$ acetone and for methanol, respectively. At 300 K the corresponding values are $0.529 \times 10^{-3}$, $0.410 \times 10^{-3}$, $0.303 \times 10^{-3}$ and $0.526 \times 10^{-3}$ Kg s$^{-1}$m$^{-1}$, respectively. [c] When not otherwise specified, the measurements were carried out with the $^1$H NMR resonances. [d] [**3**][Δ-**1**] and [**3**][Δ-**2**] were not measured in acetone[D$_6$] at 5 mM concentration. [**3**][PF$_6$] is not soluble in acetone[D$_6$] at 10 mM. [e] Saturated solutions (approx. 1 mM). [f] This value represents an average. The actual numbers for the two diastereomers are given in footnotes g–l. [g] 5.42 and $5.40 \times 10^{-10}$ m$^2$s$^{-1}$. [h] 8.57 and $8.62 \times 10^{-10}$ m$^2$s$^{-1}$. [i] 4.64 and $4.70 \times 10^{-10}$ m$^2$s$^{-1}$. [j] 4.87 and $4.95 \times 10^{-10}$ m$^2$s$^{-1}$. [k] 8.17 and $8.05 \times 10^{-10}$ m$^2$s$^{-1}$. [l] 5.40 and $5.40 \times 10^{-10}$ m$^2$s$^{-1}$. [m] The anion was not measured at these lower concentrations due to the low sensitivity of $^{31}$P in PGSE measurements. [n] $^{31}$P-PGSE diffusion measurements give similar results as the $^1$H-PGSE measurements ($D = 4.60 \times 10^{-10}$ m$^2$s$^{-1}$ in CDCl$_3$, $7.02 \times 10^{-10}$ m$^2$s$^{-1}$ in CD$_2$Cl$_2$ and $10.7 \times 10^{-10}$ m$^2$s$^{-1}$ in acetone[D$_6$]). [o] Saturated solution (ca. 5 mM).

Table 2. $D$ [$\times 10^{10}$ m$^2$s$^{-1}$] and $r_H$ [Å][a,b] values for [**4**][Δ-**1**], [**4**][Δ-**2**] and [**4**][PF$_6$].

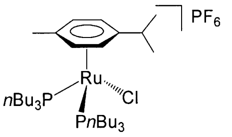
| | | | $D$ | $r_H$ | $D$ | $r_H$ | $D$ | $r_H$ | $D$ | $r_H$ |
|---|---|---|---|---|---|---|---|---|---|---|
| Salt | Concn [mM] | Fragment[c] | CDCl$_3$ | | CD$_2$Cl$_2$ | | acetone[D$_6$] | | MeOD[d] | |
| [**4**][Δ-**1**] | 5 | cation | 5.38 | 7.6 | 8.99 | 5.9 | | | | |
| | | anion ($^{31}$P) | 5.50 | 7.5 | 7.90 | 6.7 | | | | |
| | 1 | cation | 5.68 | 7.2 | 9.57 | 5.5 | 13.3 | 5.4 | 8.16 | 5.0 |
| | | anion[e] | | | | | | | | |
| [**4**][Δ-**2**] | 5 | cation[f] | | | | | | | | |
| | | anion | 5.17 | 8.0 | 7.19 | 7.4 | | | | |
| | 5 | cation$^1$ | 1.57 | 7.9 | 2.85 | 6.1 | | | | |
| | | cation$^2$ | 1.56 | 8.0 | 2.68 | 6.5 | | | | |
| | | anion | 1.58 | 7.9 | 2.34 | 7.4 | | | | |
| | 1 | cation[f] | | | | | | | | |
| | | anion | 5.65 | 7.3 | 7.73 | 6.8 | 10.9 | 6.5 | 5.83 | 7.0 |
| [**4**][PF$_6$][g] | 5 | cation | | | 10.3 | 5.1 | | | | |
| | | anion ($^{19}$F) | | | 12.8 | 4.1 | | | | |
| | 1 | cation | | | 10.7 | 4.9 | 13.5 | 5.3 | 7.97 | 5.0 |
| | | anion ($^{19}$F) | 7.84[h] | 5.2 | 13.5 | 3.9 | 26.7 | 2.6 | 16.0 | 2.6 |

[a] We propose a standard deviation of $\pm 0.06 \times 10^{-10}$ m$^2$s$^{-1}$ for $D$ values and ±0.1 Å for $r_H$ values. [b] For the calculation of $r_H$, the viscosity of the non-deuterated solvent at the temperature of the measurements (229, 299 or 300 K) was used. [18] The values at 229 K are $1.35 \times 10^{-3}$ Kg s$^{-1}$m$^{-1}$ for CHCl$_3$ and $0.964 \times 10^{-3}$ Kg s$^{-1}$m$^{-1}$ for CH$_2$Cl$_2$. [c] Cation$^1$ and cation$^2$ refer to the two different diasteromeric salts and correspond to the (*S*,*S*) and (*R*,*R*) conformers respectively. When not otherwise specified, the measurements were carried out with the $^1$H NMR resonances. [d] Saturated solutions (approx. 1 mM). [e] The anion was not measured at these lower concentrations due to low sensitivity of $^{31}$P in PGSE measurements. [f] This value was not possible to measure, as the $^1$H signals were either broad or overlapped with those of the anion. [g] Scarcely soluble in CDCl$_3$. Only the anion can be measured in this solvent, as the signals of the cation are too weak. [h] Less than 1 mM.

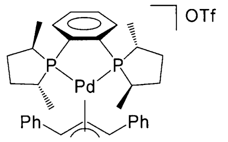
$PF_6^-$ and $CF_3SO_3^-$ ions diffuse at about the same rate as their cations.

From the chloroform and dichloromethane diffusion data in Tables 1 and 2 for the BINPHAT salts [**3**][Δ-**2**] and [**4**][Δ-**2**] and, less markedly, for the TRISPHAT salts [**3**][Δ-**1**] and [**4**][Δ-**1**], one finds, again, the same type of solvent dependence. Specifically, for [**3**][Δ-**2**] in the 1 mM solutions, the cationic hydrodynamic radius is much larger in CDCl$_3$ than in CD$_2$Cl$_2$ (7.7 Å versus 5.9 Å). The corresponding values for the anion are 7.8 Å and 6.9 Å, respectively.

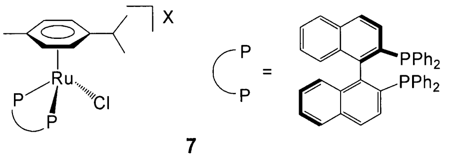
The methanol data are important in that they provide a rough estimate of the size of the strongly solvated and independently moving anions and cations.[6d] For the cations in methanol, the $r_H$ values are independent of the anion. For



**5**



**6**



**7**

example, for cation **3** we find radii of 5.3 Å, 5.2 Å and 5.2 Å for the 1 mM solutions of the three salts in Table 1. For cation **4**, the $r_{\mathrm{H}}$ value in methanol is 5.0 Å in both measured salts. Turning to the anions, the solvated BINPHAT anion, Δ-**2**, has an $r_{\mathrm{H}}$ of 7.0 Å in both [**3**][Δ-**2**] and [**4**][Δ-**2**], whereas the radii of the $PF_6^-$ ion in methanol are 2.7 Å in [**3**][$PF_6$] and 2.6 Å in [**4**][$PF_6$] (in agreement with our results for other $PF_6$ salts in methanol).[6a,d]

In 1 mM acetone solutions the $r_{\mathrm{H}}$ values for the cations **3** (5.6–5.8 Å) and **4** (5.3–5.4 Å) do not vary significantly with the nature of the anion. Similarly, the $r_{\mathrm{H}}$ values for the anions Δ-**2** (6.5 Å) and $PF_6^-$ (2.7 Å) are independent of the nature of the cation. We believe that the cations appear to be larger in acetone than in methanol due to different solvation effects.

**Asymmetric ion pairing**: As noted above, there are two diastereomers for the BINPHAT salt [**4**][Δ-**2**] with significantly different populations in dichloromethane (ca. 1.6:1) and chloroform (ca 4.6:1) at 229 K. The cations in the two diastereomers (cation$^1$ and cation$^2$ in Table 2) afford well-resolved proton signals at 229 K, so that their respective diffusion coefficients are obtainable (see Figure 1). These *D* values in dichloromethane differ by about 6%, a significant variation that lies outside the experimental error. This result is reproducible over seven different measurements, with the average *D* values for the cations in the two diasteromers being 2.85 and $2.68\times10^{-10}\,\mathrm{m^2s^{-1}}$. The upper part of Figure 1 shows two of the measurements for the cation of [**4**][Δ-**2**], with different NMR parameters. The cation in the less abundant diastereomer (white circles) moves faster (larger slope, larger *D* value) than the cation in the more abundant diastereomer (black circles). We believe this to be the first reported example of the dependence of a *D* value on diastereomeric structure. The different *D* values for the two cations, in dichloromethane, possibly arise from differing degrees of ion pairing within the two diastereomeric salts (a stronger interionic interaction producing a slower motion).

The lower part of Figure 1 shows PGSE measurements on the cation of salt [**3**][Δ-**2**] in dichloromethane. For this compound there is no difference in population between the two diastereomeric salts, whether at room temperature or at low temperature. The figure shows that the cations in these two diastereomers have exactly the same *D* value.

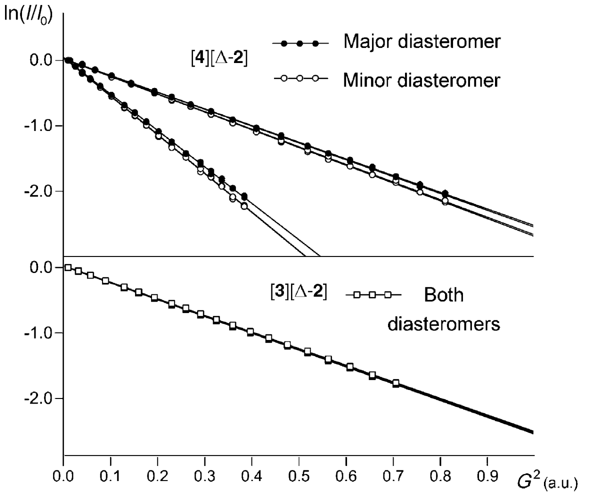


Figure 1. Plot of ln($I/I_o$) versus arbitrary units proportional to the square of the gradient amplitude for $^1$H-PGSE diffusion measurements on the cations of [**4**][Δ-**2**] (top) and [**3**][Δ-**2**] (bottom) in $CD_2Cl_2$. The differences in *D* between the diastereomers for [**4**][Δ-**2**] are visible, whereas the two diasteromers for [**3**][Δ-**2**] diffuse identically. The results of two different measurements on [**4**][Δ-**2**], with different NMR parameters, are shown. Both were carried out at 229 K. Each line results from the overlapping of measurements on two resonances of the corresponding diasteromer.

Interestingly, in chloroform, the difference in *D* value between the two diastereomers of [**4**][Δ-**2**] *vanishes* (see Table 2), although the difference in population is larger than in dichloromethane. Once the solvent promotes complete ion pairing, the structural effect on the mobility of the ions seems to be negligible.[22]

Finally, we would like to note the excellent agreement between the $r_{\mathrm{H}}$ values for the anion in [**4**][Δ-**2**] at 229 K (7.9 Å) and at room temperature (7.9 Å, see Table 2). This is a sign of the successful suppression of convection currents in the low-temperature measurements.[7]

Concluding these sections, the *D* values obtained by means of the multinuclear PGSE NMR approach allow an interesting view of ion pairing between the organic cations and the novel TRISPHAT and BINPHAT anions, which would be difficult to obtain using other methods. The diffusion data are sensitive enough to recognise a subtle diastereomeric structural effect on ion translation, as well as both solvent and concentration effects.

**Equilibria**: It would be useful to be able to estimate the amount of ion pairing in dichloromethane for our various salts, as this solvent is widely used. If the (solvated) ions, $A^+$ and $B^-$, at equal concentration (*c*), associate in dichloromethane to form an ion pair, AB, with population *p*, it can be assumed that the measured *D* value for a cation or anion in dichloromethane should be the weighted average of the contribution from the tight ion pair, AB, and from the (solvated) ions, $A^+$ or $B^-$, as shown in Equation (2).

The *D* values for the ion pairs in $CD_2Cl_2$ can be estimated from their *D* values in $CDCl_3$, correcting for the different viscosities of the two solvents. For the *D* values of the (solvated) ions in $CD_2Cl_2$, one might try to use the *D* values in

$$\begin{array}{ccccc} A^+ & + & B^- & \rightleftharpoons & AB \\ c(1-p) & & c(1-p) & & cp \end{array}$$

$$\begin{aligned} D_{\text{measured}}(A^+) &= pD(AB) + (1-p)D(CH_2Cl_2\text{-solvated } A^+) \\ D_{\text{measured}}(B^-) &= pD(AB) + (1-p)D(CH_2Cl_2\text{-solvated } B^-) \end{aligned} \quad (2)$$

MeOH. These are, however, not adequate, as they correspond to strongly solvated ions.

Consequently, we have tried to estimate the *D* values for the ions in $CD_2Cl_2$ from their ionic radii using Equation (1). The ionic radii can be derived from crystallographic data and molecular models. Modern modelling programs, such as Chem 3D®, allow the calculation of the Connolly solvent-excluded volume of a molecule ($V_{con}$), which is the volume within the surface created when a probe sphere, representing the solvent, is rolled over the molecular model.[23] Assuming the molecules to be spherical (clearly not correct), a radius $r_{con}$ can be calculated from $V_{con}$. These $r_{con}$ values will tend to be smaller than the $r_H$ values, as they do not take solvation into account.[24] Nevertheless, we have attempted to use them.[25]

For the anions Δ-**1** and Δ-**2**, the $r_{con}$'s have been estimated using both X-ray data and a molecular model as input for Chem 3D® (the model was optimised by the program by a molecular mechanics energy minimisation). Both inputs afford the same $r_{con}$ for Δ-**1** (4.9 Å) and similar values for Δ-**2** (5.3 Å (X-ray) and 5.2 Å (model)). We note that the estimated $r_{con}$ for Δ-**2** (ca. 5.2 Å) is considerably smaller than the $r_H$ value in methanol (7.0 Å). This is logical, as the 7.0 Å value corresponds to the strongly solvated and/or hydrogen-bonded anion.

For the cations **3** and **4** the molecular models afford $r_{con}$ values of 4.7 Å and 4.4 Å, respectively. These radii are again smaller than the $r_H$ values in methanol (ca. 5.2 Å for **3** and 5.0 Å for **4**), although the difference is not as large as for the anion Δ-**2**.[26] Finally, for the $PF_6^-$ ion, the estimated $r_{con}$ (2.5 Å) is in good agreement with the $r_H$ in methanol (2.7 Å).[27]

The *p* values shown in Table 3 are obtained by putting the $r_{con}$ values noted above into Equation (1), then introducing the resulting *D* values for the ions into Equation (2). We have restricted this exercise to the four cases shown, for which we have the most complete data set. Clearly, these *p* values are gross estimates and they constitute upper limits, as $r_{con}$ does not include the solvation shell of the ions. Nevertheless, and in spite of the crude assumptions made, these *p* values can still be informative. Firstly, in all cases, there seems to be a significant amount of ion pairing in $CD_2Cl_2$.[28] Secondly, there seems to be more ion pairing in both Δ-**2** salts than in both Δ-**1** salts.[29] Thirdly, the difference in *p* value between cation and anion (e.g., 0.62 vs 0.73 in [**3**][Δ-**2**]) suggests, reasonably enough, that there are different solvation effects for the two species.[26] If one were to make a correction for the lack of solvation sphere, the amount added to $r_{con}$ would be different for the cation and anion. We know of no other physical method that would readily reveal this type of difference.

Table 3. *p* values for 10 mM [**3**][Δ-**1**], [**3**][Δ-**2**], [**4**][Δ-**1**] and [**4**][Δ-**2**].[a]

| Salt | | *p* values |
|---|---|---|
| [**3**][Δ-**1**] | cation | 0.56 |
| | anion | 0.61 |
| | average | **0.58** |
| [**3**][Δ-**2**] | cation | 0.62 |
| | anion | 0.73 |
| | average | **0.67** |
| [**4**][Δ-**1**] | cation | 0.62 |
| | anion | 0.77 |
| | average | **0.69** |
| [**4**][Δ-**2**] | cation$^1$ | 0.60 |
| | cation$^2$ | 0.68 |
| | anion | 0.82 |
| | average$^1$ | **0.71** |
| | average$^2$ | **0.75** |

[a] Cation$^1$ and cation$^2$ refer to the two different diasteromeric salts and correspond to the (*S*,*S*) and (*R*,*R*) conformers, respectively.

## Conclusion

Evidently, both organic and transition-metal salts reveal a dependence of their *D* values on solvent and concentration. In both the Δ-**1** and Δ-**2** salts, chloroform promotes strong ion pairing. In $CD_2Cl_2$ the ion pairing is not complete and, in two Δ-**2**-based diastereomers, the ion pairing is selective enough to be recognised through different *D* values. Although the PGSE approach to recognizing ion pairing is facile, the picture provided is only crude. Nevertheless, with the help of these data, this subject can be discussed in a more rational and less speculative fashion.

## Experimental Section

The compounds [**3**][Δ-**1**], [**3**][Δ-**2**], [**3**][$PF_6$], [**4**][Δ-**1**], [**4**][Δ-**2**] and [**4**][$PF_6$] were prepared by previously reported procedures.[15e,16]

**Diffusion measurements**: PGSE measurements made use of a spin-echo sequence in which two pulsed field gradients had been incorporated (Stejskal–Tanner sequence).[30,31] Molecular translation caused attenuated signal intensities, as the molecules did not experience the same field strength when the second refocusing gradient was applied. The experiment was repeated with increasing gradient strength (*G*) and the *D* value was determined from the slope of the regression line $\ln(I/I_o)$ versus $G^2$, according to Equation (3) in which *I* is the observed intensity, $I_o$ is the intensity without gradients, $\gamma$ is the gyromagnetic ratio of the observed nucleus, $\delta$ is the length of the gradient pulse, *G* is the gradient strength, $\Delta$ (diffusion delay) is the delay between the midpoints of the gradients and *D* is the diffusion coefficient

$$\ln\left(\frac{I}{I_o}\right) = -(\gamma\delta)^2\left(\Delta - \frac{\delta}{3}\right)DG^2 \quad (3)$$

A frequently employed modification of the Stejskal–Tanner sequence, the so-called stimulated echo experiment, splits the π pulse into two π/2 pulses.[31]

All the measurements were performed on Bruker AVANCE spectrometers (300, 500 MHz) equipped with a microprocessor controlled gradient unit and a multinuclear probe (normal or inverse) with an actively shielded Z-gradient coil. The shape of the gradient pulse was rectangular and its strength varied automatically in the course of the experiments. The calibration of the gradients on each spectrometer was carried out by means of a diffusion measurement of HDO in $D_2O$ ($D_{HDO} = 1.9 \times 10^{-9}$ $m^2 s^{-1}$).[32]

For the $^1H$ and $^{19}F$ measurements, $\delta$ was set to 1.25–3.5 ms and $\Delta$ was between 30 and 170 ms. The gradient strength was usually incremented in steps of 3 or 4 %, so that 15–25 points could be used for regression analysis. The number of scans per increment varied between 8 and 48, depending on the concentration, spectrometer and nucleus. For $^{19}F$, $T_1$ was always determined before the measurement, and the recovery delay set to 5 $T_1$. For $^1H$, this delay was always set to 5 s. Typical total experimental times were 0.5–2 h for $^1H$ and 2–4 h for $^{19}F$ spectra.

For the $^{31}P$ measurements, $\delta$ was set to 1.75 ms and $\Delta = 268$ or 468 ms.[5] The gradient strength was usually incremented in steps of 8–12 %, so that 10–12 points could be used for regression analysis. As the $T_1$ values were long (20–30 s), the relaxation delay was set to 2–3 times $T_1$ and 28–72 scans were accumulated per increment. Typical total experimental times were between 8–16 h.

The measurements on the two diastereomers in [**3**][Δ-**1**], ([**3**][Δ-**2**], and [**4**][Δ-**2**] were carried out in the 500 MHz machine with the Stejskal–Tanner pulse sequence. This sequence resulted in a better shape and intensity of the resolved multiplets of each diastereomer. The evolution time before and after the 180° pulse was set to about 1/(2 *J*). For the ammonium cation **4**, the $^2J_{(H,H)}$ value, 13 Hz, was used, whereas for the remaining ions, a $^3J_{(H,H)}$ value of 8 Hz was employed. The number of scans was between 16 and 36. For the rest of the experiments the stimulated echo pulse sequence was used.

To avoid convection in the low-temperature $^1H$-PGSE measurements on [**4**][Δ-**2**], a set-up consisting of two commercially available coaxial NMR tubes, separated by air and kept concentrical by a pyrex spacer, was employed.[7] The inner tube had an internal diameter of 1.96 mm and an external diameter of 2.97 mm. A standard 5 mm vessel was used for the outer tube. Due to the smaller volume of sample, the number of scans was set to about 100 and the total experimental time was 2–3 h. The $\delta$ values were higher than at room temperature (3–4 ms), to compensate for the decreased mobility of the molecules at low temperature.

All of the observed data leading to the reported *D* values afforded lines whose correlation coefficients were above 0.999. Based on our experience from work on diffusion over several years, we propose a standard deviation of $\pm 0.06 \times 10^{-10}$ $m^2 s^{-1}$ for the *D* values and ±0.1 Å for the hydrodynamic radii.

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[20] To be consistent and facilitate comparisons we have used Equation (1) as shown. However, it is accepted that the factor 6 in Equation (1) is not valid for small species that are comparable in size to the solvent molecules. The limits for this condition are not clear, but in general when $r_{\rm solute}/r_{\rm solvent} \leq \approx 2$, the substitution of 6 by 4, or its multiplication by an empirical factor $f$ ($f < 1$), have been proposed. See, for instance: A. Gierer, K. Wirtz, *Z. Naturforsch.* **1953**, *8*, 522–532; A. Spernol, K. Wirtz, *Z. Naturforsch.* **1953**, *8*, 532–538, H. C. Chen, S. H. Chen, *J. Phys. Chem.* **1984**, *88*, 5118–5121; J. T. Edward, *J. Chem. Educ.* **1970**, *47*, 261–270; M. Ue, *J. Electrochem. Soc.* **1994**, *141*, 3336–3342.

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[25] Modelling programs also allow the calculation of a van der Waals volume ($V_{\rm vdw}$) from which a van der Waals radius ($r_{\rm vdw}$) can be derived. The $V_{\rm vdw}$ does not take into account the empty volume inside and around the ions, which is inaccessible to the solvent molecules. Consequently, $r_{\rm vdw}$ is smaller than $r_{\rm con}$, and not appropriate for comparison with $r_{\rm H}$ values. It is also possible to estimate the rotational radius of a molecule ($r_{\rm r}$), which is the radius of the sphere determined by rotating a molecular model or X-ray structure around its geometric center. The $r_{\rm r}$ values are usually too big when compared with $r_{\rm H}$. For more comments on molecular radii, see M. Ihnat, D. A. I. Goring, *Can. J. Chem.* **1967**, *45*, 2353–2361 and K. W. Mattison, U. Nobbmann, D. Dolak, *Am. Biotechnol. Lab.* **2001**, *19*, 66–68.

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[27] This 2.7 Å value for $PF_6^-$ in methanol is probably too small, see ref. [20].

[28] Decreasing the $D$ values of the ions (calculated from $r_{\rm con}$) by 10%, to allow for solvation in $CD_2Cl_2$, results in $p$ values that are only 10–20% smaller than those shown in Table 3.

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