Kinetics of proton transfer from phosphonium ions to electrogenerated bases: polar, steric and structural influences on kinetic acidity and basicity

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Derivative cyclic voltammetry (DCV) and linear sweep voltammetry (LSV) have been used to measure rates of proton transfer in DMSO solution between different types of electrogenerated base (EGB) and a series of phosphonium ions of relevance to ylide formation for synthetic reactions. Although the electrochemical methods are convenient for the measurement of rates of proton transfer in these systems a major conclusion of the study is that considerable care must be exercised in the application of the methods and in drawing general conclusions from the results. In particular, comparison of kinetic acidity with thermodynamic p*K* values in DMSO shows that a single Brønsted relationship does not hold for the series of phosphonium ions. The kinetic acidities are profoundly affected by: whether the EGB is a carbon or nitrogen base; the propensity of some of the phosphonium ions to enolise; and steric factors. Other measures of electron-demand at the acidic methylene groups (^{13}C and ^{1}H chemical shifts, reduction potentials) are consistent with the p*K*(DMSO) values. The kinetic results confirm that the Ph_3P^+ group is, for non-enolisable phosphonium salts, more activating than Bu_3P^+.

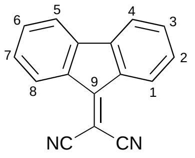
Phosphonium salts of the general formula $R_3P^+CH_2Y\ X^-$ are important in synthesis as precursors of reactive ylides, *e.g.* in the Wittig reaction. They are true carbon acids, except where Y is such that enolisation is possible; it is only recently that the thermodynamic acidity (p*K*) of a number of these salts has been determined in DMSO.[1] In practice it is often kinetic acidity which is of significance in preparative reactions; the rate at which a reactive carbanion or ylide may be formed by reaction between a base and carbon acid may determine its usefulness.

Electrogenerated bases (EGBs), formed by cathodic reduction of organic precursors (probases), have found use[2] as reagents which are easy to generate under controlled conditions and which, depending on the probase structure, cover a range of effective basicities. As part of an ongoing study of the formation and properties of EGBs the kinetics of proton transfer between carbon acids and EGBs has been studied over several years. Initially[3] it was hoped that a relationship between the rates of proton transfer and the thermodynamic p*K* values of similar acids (with known thermodynamic acidity) could be used to predict p*K* values for acids of unknown p*K*. However, this approach is fraught with difficulty because different types of acids (*e.g.* oxygen *vs.* carbon acids) have different intrinsic rate constants (defined as the statistically corrected second order rate constant for a process with zero driving force) and different Brønsted α-values.[4] For acids belonging to a single family good correlations between thermodynamic and kinetic acidities have previously been found using EGBs.[5,6]

An examination of the kinetics of proton transfer from phosphonium ions to EGBs is presented here. This allows a useful comparison, in one series and depending on the nature of Y (compounds **1a**–**h**), between acids which are not enolisable (true carbon acids) and those in which proton transfer can take place from either carbon or oxygen. Four EGBs have been used which have differing steric demands and either nitrogen or carbon basic centres; the corresponding probases are compounds **2**–**5**.

$R_3P^+CH_2YX^-$

1a R = Ph, Y = H, X = Br
1b R = Ph, Y = $CH_3(CH_2)_2$, X = Br
1c R = Ph, Y = Ph, X = Br
1d R = Bu, Y = Ph, X = Cl
1e R = Ph, Y = -CH=CHPh, X = Cl
1f R = Ph, Y = $-CO_2Et$, X = Br
1g R = Bu, Y = $-CO_2Et$, X = Br
1h R = Ph, Y = -COMe, X = Br



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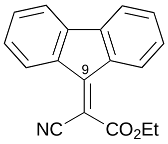

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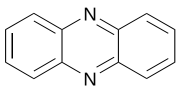

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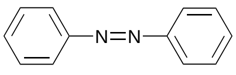

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Results and discussion

All measurements were made using DMSO as solvent since DMSO is the dipolar aprotic solvent in which the largest number of p*K* values have previously been reliably determined.[7] Voltammetric experiments on the probases and measurement of rates of proton transfer were performed at an Hg-coated Pt electrode ($d = 0.6$ mm) with Bu_4NPF_6 (0.1 M) as supporting

Table 1 Reduction potentials and p*K* values of phosphonium salts[a]

Compound	p*K*(DMSO)[b]	$-E_{p,c}(1)$/V
1a	22.5	1.989
1b		1.915
1c	17.4	1.780
1d		2.690
1e		1.741
1f	8.5	1.685
1g		2.611
1h	7.1	1.685

[a] Peak potentials with reference to SCE, measured by cyclic voltammetry at 0.1 V s^{-1}, as 1 mM solutions in DMSO–Bu_4NPF_6 (0.1 M), at a Hg/Pt electrode. [b] From ref. 1.

electrolyte. The supporting electrolyte was chosen to ensure that neither the cation nor the anion gave rise to ion-pairing with radical anions/dianions or cations in solution. Reduction potentials are given *vs*. the saturated calomel electrode (SCE).

Phosphonium ions

The phosphonium ions $R_3P^+CH_2Y$ (**1**) for which the rates of deprotonation have been measured fall into two families: those activated by Ph_3P^+ (**1a**–**c**, **1e**–**f**, **1h**) and those activated by Bu_3P^+ (**1d**, **1g**). The last family presents a special problem with respect to which proton is transferred since in addition to the CH_2-protons another six equivalent protons are available neighbouring the phosphorous atom. The phosphonium ions may be further divided into three classes: (*a*) the phosphonium group is the only activating group [$Ph_3P^+CH_3$ (**1a**), $Ph_3P^+CH_2CH_2CH_2CH_3$ (**1b**)]; (*b*) the carbon skeleton provides an additional weakly acidifying effect [$Ph_3P^+CH_2Ph$ (**1c**), $Ph_3P^+CH_2CH{=}CHPh$ (**1e**), $Bu_3P^+CH_2Ph$ (**1d**)]; (*c*) the acidic protons are doubly activated due to the presence of a strongly electron-withdrawing group in addition to the phosphonium group [$Ph_3P^+CH_2CO_2Et$ (**1f**), $Bu_3P^+CH_2CO_2Et$ (**1g**), $Ph_3P^+CH_2COMe$ (**1h**)]. For the last class of phosphonium ions another problem arises; the possibility for enolisation of the acid may change the site from which the proton transfer takes place from carbon to oxygen, and since the intrinsic rates of proton transfer from carbon and from oxygen very often differ by orders of magnitude[4] the kinetic measurements relating to this class of compounds should be treated very carefully when it comes to evaluation of relationships between thermodynamic and kinetic acidities.[8]

It is important for the proposed kinetic experiments that the EGBs are formed at higher (less cathodic) potentials than those at which the phosphonium ions are reduced. The electrochemistry of the phosphonium ions was therefore briefly examined. The data are collected in Table 1. The reduction of phosphonium ions in dipolar aprotic solvents in the absence of added acids or bases has previously been well-investigated.[9,10] The main conclusions of that work pertaining to phosphonium ions with α-protons of the general formula $R_3P^+CH_2Y$ are summarized in Scheme 1. The salient features are: (*i*) the first chemically irreversible reduction peak corresponds to a two electron process but appears as a one electron peak since half of the phosphonium ion is used as proton donor [reaction (3)]; (*ii*) the first reduction peak corresponds to cleavage of a C–P bond with rapid further reduction of the carbon radical to a carbanion. The carbanion deprotonates the starting phosphonium ion to produce a hydrocarbon (YCH_3 or RH) and an ylide, the chemically irreversible reduction of which is responsible for a second reduction peak. Further reduction peaks may be associated with reduction of triphenylphosphine (R = Ph) or of the hydrocarbon (YCH_3 or RH).

$$R_3P^+CH_2Y + e^- \xrightarrow{E_{p,c}(1)} (R_3P + {}^{\bullet}CH_2Y)/(R_2PCH_2Y + {}^{\bullet}R) \tag{1}$$

$${}^{\bullet}CH_2Y/{}^{\bullet}R + e^- \xrightarrow{>E_{p,c}(1)} {}^-CH_2Y/{}^-R \tag{2}$$

$$R_3P^+CH_2Y + {}^-CH_2Y/{}^-R \longrightarrow R_3P{=}CHY + CH_3Y/RH \tag{3}$$

$$R_3P{=}CHY + e^- \xrightarrow{E_{p,c}(2) < E_{p,c}(1)} ? \tag{4}$$

Scheme 1 Direct cathodic reduction of phosphonium ions

Table 2 Reduction potentials[a] for probases

Compound	$-E^\circ(1)$/V	$-E^\circ(2)$/V
2	0.587	1.303
3	0.710	1.235
4	1.298	
5	1.125	

[a] Formal potentials with reference to SCE, measured by cyclic voltammetry at 1 V s^{-1}, as 1 mM solutions in DMSO–Bu_4NPF_6 (0.1 M), at an Hg/Pt electrode.

In the presence of electrogenerated bases, which are generated at less cathodic potentials than those required for cathodic cleavage of the phosphonium ions, the slow and usually measurable step is the proton transfer from the phosphonium ion to the EGB. In previous studies[9,10] the linking of this step to ylide formation has been established.

EGBs and the measurement techniques

From the thermodynamic acidities in DMSO determined recently[1] for four of the phosphonium ions it appears (Table 1) that the range of acidities covered by the series is at least 15.4 p*K*-units. Since no Brønsted α-value has been determined for the deprotonation of phosphonium ions with any base, we will initially assume the Brønsted α-value to be 'normal' and in the range 0.3–0.7. As a consequence the kinetic range covered by the series of phosphonium ions with a single base is estimated to be 6–10 orders of magnitude.

A kinetic range as large as that predicted above is almost impossible to cover experimentally using a single technique and we have therefore chosen to apply two different approaches. They are: (1) the application of different EGBs with varying basicity; (2) the application of different electroanalytical techniques for a single (strong) base. The EGBs chosen are the dianions of probases **2** and **3** and the radical anions of probases **4** and **5**. They fulfil the criteria that the potential of their formation (see Table 2) is higher (less cathodic) than the potential at which the phosphonium ions are reduced. Furthermore the dianions of probases **2** and **3** and the radical anions of probases **4** and **5** are stable in the absence of proton donors on timescales corresponding to scan rates down to 0.1 V s^{-1}. Upon addition of an excess of appropriately acidic phosphonium salts the chemical reversibility of the EGB generating reduction is partially or completely lost and the reduction peak height increases for **4** and **5**.

The two types of EGBs differ in a number of ways: (*a*) in the dianions derived from **2** and **3** the site of protonation is expected to be a carbon atom whereas in the two radical anions derived from **4** and **5** the site of protonation is a nitrogen atom; (*b*) the proton transfer to the dianions [reaction (8) in Scheme 2] may in principle be reversible on the timescale of the measurements. This is because neither of the products (the more stable

$$PB + e^- \overset{E^\circ(1)}{\rightleftharpoons} PB^{\bullet -} \tag{5}$$

$$PB^{\bullet -} + e^- \overset{E^\circ(2)}{\rightleftharpoons} PB^{2-} \tag{6}$$

$$PB + PB^{2-} \overset{K_7}{\rightleftharpoons} 2\,PB^{\bullet -} \tag{7}$$

$$PB^{2-} + R_3P^+CH_2Y \xrightarrow{k} PBH^- + R_3P{=}CHY \tag{8}$$

Scheme 2 Deprotonation of phosphonium salts by the EGBs $\mathbf{2}^{2-}$ or $\mathbf{3}^{2-}$ by an (E)EC mechanism ylides and the monoanions PBH$^-$ equate to **2H**$^-$ or **3H**$^-$) are consumed in fast follow-up reactions under the conditions of the measurements, whereas the neutral radicals formed by protonation of the radical anions of **4** and **5** are further reduced and subsequently protonated in a normal DISP1 reaction (Scheme 3), rendering the initial proton transfer essentially irreversible.

$$\mathrm{PB} + e^- \rightleftharpoons \mathrm{PB}^{\bullet -} \qquad (9)$$

$$\mathrm{PB}^{\bullet -} + \mathrm{R_3P^+CH_2Y} \xrightarrow{k} \mathrm{PBH}^{\bullet} + \mathrm{R_3P{=}CHY} \qquad (10)$$

$$\mathrm{PBH}^{\bullet} + \mathrm{PB}^{\bullet -} \xrightarrow{\text{fast}} \mathrm{PBH}^- + \mathrm{PB} \qquad (11)$$

$$\mathrm{PBH}^- + \mathrm{R_3P^+CH_2Y} \xrightarrow{\text{fast}} \mathrm{PBH_2} + \mathrm{R_3P{=}CHY} \qquad (12)$$

Scheme 3 Deprotonation of phosphonium salts by the EGBs $\mathbf{4}^{\bullet -}$ or $\mathbf{5}^{\bullet -}$ by a DISP1 mechanism

The possible reversibility of protonation of the dianions of **2** and **3** limits their applicability for simple, uncomplicated measurements of pure proton transfer rate constants. A driving force for the proton transfer reaction large enough to make the back reaction insignificant on the timescale of the measurements is required for a simple (E)EC scheme to be adequate, *i.e.* only the more acidic phosphonium ions can be used with these EGBs. On the other hand very acidic phosphonium ions cannot be studied since eventually they will be able to protonate the radical anions of **2** and **3** and thereby invalidate the measurements.

Rates of proton transfer from carbon or oxygen acids to radical anions or dianions have previously been made using linear sweep voltammetry (LSV),[11] cyclic voltammetry,[5,12] derivative cyclic voltammetry[6,13] (DCV) and double potential step chronoamperometry (DPSC).[3,5,13–15] The method used must be carefully chosen. For instance, it is now clear that DPSC is unsuitable for use with the phosphonium ions using the dianions of **2** and **3** because the method involves stepping cathodically to potentials at which direct reduction of the phosphonium ion may take place. We now believe that earlier measurements for phosphonium ions using this method[15] are unreliable. The applicability of the LSV method is also limited since determination of rate constants is only possible when the electrochemical process is under purely kinetic control, *i.e.* the rates of electron and proton transfers must be relatively high.

In this study we have chosen to use DCV[16] as the main technique, and in order to check whether the acid–base systems are well-behaved and indeed follow the mechanisms in Schemes 2 and 3 we have chosen to record the values of R_I' [$R_\mathrm{I}' = -i_\mathrm{p}'(\mathrm{ox})/i_\mathrm{p}'(\mathrm{red})$, where $i_\mathrm{p}'(\mathrm{ox})$ and $i_\mathrm{p}'(\mathrm{red})$ are the heights of the peaks of the derivative of the current] over a broad range of scan rates (v) and to examine the fit of the experimental data [R_I' *vs.* $-\log(v)$] to the theoretical working curve for the assumed mechanism. In most cases two or more concentrations of the phosphonium salt were used for this type of measurement, and the rate constants calculated from the fit of experimental to theoretical data (see Experimental section).

When the rest potential from which the cathodic scan is initiated is anodic relative to the first reduction of probases **2** or **3**, the mechanism includes all the reactions in Scheme 2 in an EEC process. Accordingly, the theoretical data necessary to calculate the rate constant, k, for the proton transfer must include the electron transfer reaction between the dianion and the substrate [reproportionation, reaction (7)], the equilibrium constant for which depends on whether **2** or **3** is used as probase due to the difference in their values of $\Delta E^\circ = E^\circ(1) - E^\circ(2)$, *i.e.* $K_7 = \exp[(F\Delta E^\circ)/(RT)]$. This way of making the measurements is called method 1 in the following discussion. Since the radical anions derived from probases **2** or **3** are stable in the absence of strong proton donors, the measurements may be made in a simpler way if the rest potential is chosen to be between the two potentials for consecutive reduction of **2** or **3**. Due to the stability of the radical anions, **2** or **3** are completely converted into the corresponding radical anions in the diffusion layer next to the electrode which will be completely depleted of **2** or **3**. The mechanistic scheme is therefore considerably simplified (to an EC mechanism) since only reactions (6) and (8) in Scheme 2 need to be considered when calculating the theoretical data necessary to obtain the rate constant for the proton transfer. This way of making the measurements will be referred to as method 2. The quantities measured for each of the two methods are outlined in Fig. 1, and both methods were applied for most of the phosphonium salts studied using **2** or **3** as probases. The stability of the radical anions $\mathbf{2}^{\bullet -}$ or $\mathbf{3}^{\bullet -}$ in the presence of the phosphonium salts was always checked by confirming that $R_\mathrm{I}'(1) \approx 1$ even at low scan rates, when the scan was reversed between the two reduction peaks.

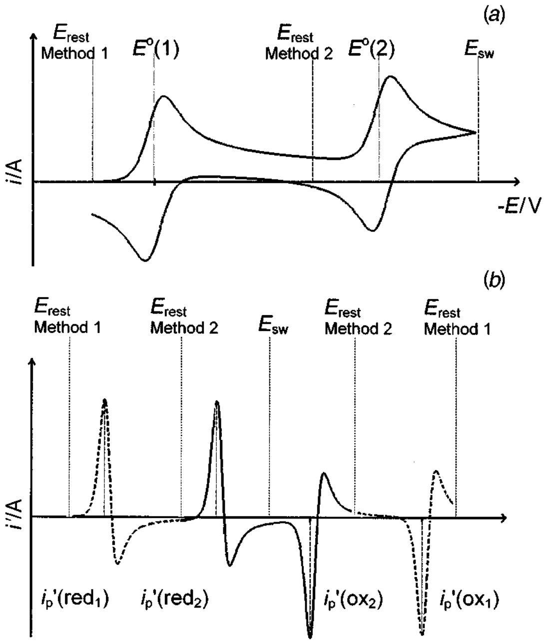

Fig. 1 Methods adopted for kinetic measurements using probases **2** and **3**. (*a*) Choice of rest potential indicated on a normal CV. (*b*) Derivative cyclic voltammogram (i' *vs.* t) for method 1 (broken line) and method 2 (full line). For both methods the quantity determined is $R'_\mathrm{I}(2) = -i'_\mathrm{p}(\mathrm{ox}_2)/i'_\mathrm{p}(\mathrm{red}_2)$.

For probases **4** and **5** only a single electron transfer is involved and the data are analyzed according to theoretical data for the DISP1 mechanism in Scheme 3. For some of the proton transfer reactions (see below) involving $\mathbf{4}^{\bullet -}$ and $\mathbf{5}^{\bullet -}$ the rate was so high that DCV was inconvenient, and the rate constants were therefore determined by LSV, *i.e.* by measuring the values of $E_\mathrm{p} - E^\circ$ at several scan rates followed by application of eqn. (13) pertaining to the mechanism in Scheme 3.[17]

$$k = \frac{nFv}{RT} \exp\left[\frac{2nF}{RT}(E_\mathrm{p} - E^\circ) + (2 \times 0.783) + \ln 2\right] \qquad (13)$$

Kinetic results and the influence of experimental difficulties

The results of the kinetic measurements for the series of phosphonium salts and the four EGBs are summarised in Table 3. In general the rate constants determined by methods 1 and 2 using $\mathbf{2}^{2-}$ and $\mathbf{3}^{2-}$ as EGBs were identical within the experimental error. Before discussing the data it is proper to consider in detail the measurements which lead to the values given in Table 3.

Measurements using $\mathbf{2}^{2-}$ as EGB. There are only three numbers in Table 3 for this EGB. The least acidic salts do not react on the timescale of the measurements, and an additional problem was encountered when using $\mathbf{2}^{2-}$ as the base for

Table 3 Rate constants, k_{EGB} in $M^{-1}\ s^{-1}$, for proton transfer in DMSO[a]

$R_3P^+CH_2Y$ (**1**)	$\mathbf{2}^{2-}$	$\mathbf{3}^{2-}$	$\mathbf{4}^{\bullet -}$	$\mathbf{5}^{\bullet -}$
1a, R = Ph, Y = H		[12.31][b] {8.25}[c]	(1.9 ± 0.1) × 10^{2}[d] {1.27 × 10^{2}}[c]	(2.4 ± 0.4) × 10^{3}[d] {1.61 × 10^{3}}[c]
1b, R = Ph, Y = $CH_3(CH_2)_2$		[13.15][b]	(2.1 ± 0.2) × 10^{2}[e]	(2.8 ± 0.5) × 10^{3}[f]
1c, R = Ph, Y = Ph		(4 ± 2) × 10^{1}[g]	(1.6 ± 0.1) × 10^{3}[d]	(2.7 ± 0.2) × 10^{3}[h]
1d, R = Bu, Y = Ph				(1.8 ± 0.2) × 10^{1}[i]
1e, R = Ph, Y = PhCH=CH		(3.8 ± 0.1) × 10^{2}[j]	(2.1 ± 0.1) × 10^{4}[e]	
1f, R = Ph, Y = EtO_2C	(6.6 ± 0.3) × 10^{4}[k]	(1.6 ± 0.2) × 10^{5}[l]	(2.8 ± 0.2) × 10^{8}[m]	
1g, R = Bu, Y = EtO_2C	(5.0 ± 0.5) × 10^{4}[l]	(3.2 ± 0.2) × 10^{4}[n]	(4 ± 1) × 10^{7}[o]	
1h, R = Ph, Y = CH_3CO	4.3 × 10^{5}[p]	(4.6 × 10^{5})[q]		

[a] C^o(probase) = 1 mM, $t = 22 \pm 2$ °C, Hg/Pt working electrode, $E^o(2) - E_{sw} = 0.3$ V for **2** and **3**, $E^o(1) - E_{sw} = 0.3$ V for **4** and **5**. DMSO–Bu_4NPF_6 (0.1 M). [b] By extrapolation—see Fig. 3. [c] Corrected for number of acidic protons, *i.e.* ×0.67. [d] C^o(HB) = 10 mM, average of rate constants determined by fit to working curve (DISP1) and from the $v_{0.5}$-value. [e] C^o(HB) = 10 and 20 mM, average of rate constants determined by fits to working curve (DISP1) and from $v_{0.5}$-values. [f] C^o(HB) = 10 and 20 mM, average of rate constants determined from $v_{0.5}$-values (DISP1). [g] C^o(HB) = 80 mM, average of rate constants determined from $v_{0.5}$-values (methods 1 and 2). [h] C^o(HB) = 10, 20 and 40 mM, average of rate constants determined by fits to working curve (DISP1) and from $v_{0.5}$-values. [i] C^o(HB) = 40 mM, average of rate constants determined by fit to working curve (DISP1) and from $v_{0.5}$-value. [j] C^o(HB) = 10 and 40 mM, average of rate constants determined by fits to working curve and from $v_{0.5}$-values (method 1). [k] C^o(HB) = 10 mM, average of rate constants determined by fit to working curve and from $v_{0.5}$-value (method 1). [l] C^o(HB) = 10 mM, average of rate constants determined by fits to working curves and from $v_{0.5}$-values (methods 1 and 2). [m] C^o(HB) = 20 mM, rate constant determined from values of $E_p - E^o$ measured at $0.1 - 1.0\ V\ s^{-1}$ and eqn. (13). [n] C^o(HB) = 10 and 20 mM, average of rate constants determined by fits to working curves and from $v_{0.5}$-values (methods 1 and 2). [o] C^o(HB) = 10 and 20 mM, average of rate constants determined by LSV at $v = 0.5$, 1 and 2 V s^{-1} (DISP1). [p] C^o(HB) = 1 mM, rate constant determined by fit to working curve (method 1). [q] C^o(HB) = 10 mM, rate constant determined by fit to working curve (method 1) for $v = 100$–800 V s^{-1}.

phosphonium ions of intermediate acidity: the working curves become too steep at low scan rates (*i.e.* the problem is serious for weak acids) apparently due to some kind of acid-catalysed tautomerisation of the dianion leading to a splitting of the oxidation peak into two peaks. The problem is not related to the phosphonium ions since the same phenomenon was observed for other types of weak acids as well. The new peak is at a slightly more anodic potential than the original one. The consequence is an artificially fast decrease of the height of the original oxidation peak with decreasing scan rate thereby invalidating measurements on this timescale. The group of phosphonium ions of intermediate acidity caused the above mentioned peak splitting at low scan rates and results from these measurements are therefore excluded. The rate constants obtained using **1g** and **1f**, $R_3P^+CH_2CO_2Et$ (R = Bu, Ph), are based on measurements with only a single concentration of the acid (10-fold excess) due to the high rate of the reactions. The fits to the working curves are good for both compounds and the rate constants obtained are surprisingly similar. The data obtained for **1h**, $Ph_3P^+CH_2COCH_3$, are questionable. Since the rate constant for proton transfer is high, data for working curve fit by method 1 (rest potential anodic to the first reduction) could only be obtained using equimolar concentrations of phosphonium salt and probase.

Measurements using $\mathbf{3}^{2-}$ as EGB. This EGB does not cause the problem encountered for $\mathbf{2}^{2-}$ with splitting of the oxidation peak and $\mathbf{3}^{2-}$ appears to be slightly more basic than $\mathbf{2}^{2-}$. A larger number of rate constants could therefore be determined. Compound **1c**, $Ph_3P^+CH_2Ph$, reacts very slowly with $\mathbf{3}^{2-}$, the R_I' *vs.* −log(v) plots at low concentration of **1c** are too flat compared with the working curves, and the apparent reaction order in phosphonium salt is larger than unity. This behaviour indicates reversibility in the proton transfer reaction on the timescale of the measurements.[18] The better fits of the experimental data to the working curves are therefore obtained at a high concentration of **1c** (80 mM) where the proton transfer equilibrium is displaced towards the products. The analogous compound **1d**, $Bu_3P^+CH_2Ph$, is unreactive towards $\mathbf{3}^{2-}$. The data obtained for **1e**, $Ph_3P^+CH_2CH$=CHPh, give acceptable fits to the working curves for both methods. In contrast to the results obtained using $\mathbf{2}^{2-}$ as EGB, the rate constants determined for reaction between $\mathbf{3}^{2-}$ and the compounds **1g** and **1f**, $R_3P^+CH_2CO_2Et$ (R = Ph, Bu), differ by a factor of five. In both cases the quality of the data is good as seen in Fig. 2, which demonstrates the data treatment by fit to working curves for the two methods. The high acidity of **1h**, $Ph_3P^+CH_2COCH_3$, presents a problem using **3** as probase since protonation of the radical anion, $\mathbf{3}^{\bullet -}$, takes place at low scan rates. Using a 10-fold excess of **1h** and scan rates in the range 100–800 V s^{-1} only allows an uncertain estimate of the rate constant by method 1 since a very limited part of the working curve is accessible.

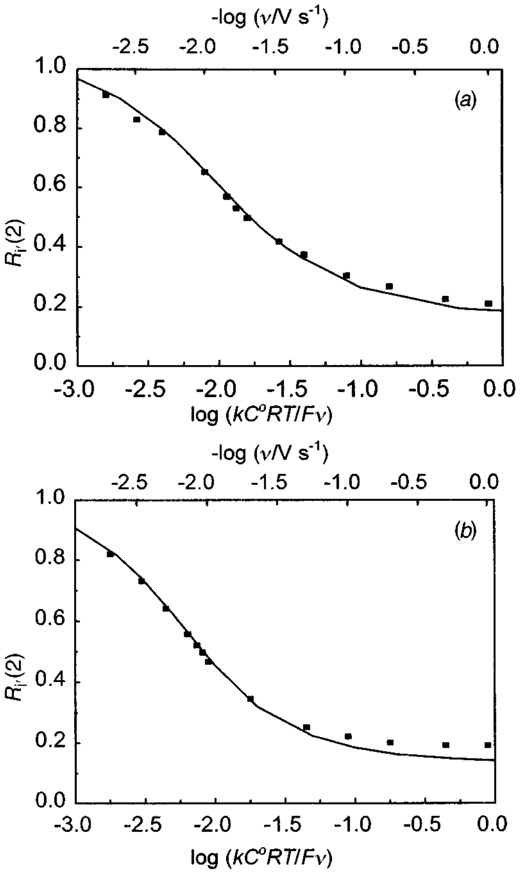

Fig. 2 Fit of experimental DCV data obtained for **1g** (10 mM) using **3** (1 mM) as probase in DMSO (0.1 M Bu_4NPF_6) to working curves for (*a*) method 1, based on $\Delta E^o = E^o(1) - E^o(2) = 0.52$ V and (*b*) method 2. In both cases $E^o(2) - E_{sw} = 0.3$ V.

Measurements using $\mathbf{4}^{\bullet -}$ as EGB. The least acidic phosphonium cations do not protonate either of the dianionic EGBs derived from **2** and **3** on the timescale of the measurements, and therefore the faster reacting radical anions derived from phenazine (**4**) and azobenzene (**5**) were used for reaction with weakly acidic cations. Using $4^{\bullet-}$ as an EGB allows determination of the kinetic acidity of all the thermodynamically weak phosphonium cations—except for **1d**, $Bu_3P^+CH_2Ph$, which does not react on the timescale of the measurements. However, the quality of the data varies considerably; good fits to the working curve for the DISP1 mechanism (Scheme 3) are obtained for **1a**, $Ph_3P^+CH_3$, and **1e**, $Ph_3P^+CH_2CH{=}CHPh$, in contrast to the poor fits obtained for the salts **1b** and **1c**, $Ph_3P^+CH_2CH_2CH_2CH_3$ and $Ph_3P^+CH_2Ph$. For the most acidic phosphonium cations the rates of protonation of $4^{\bullet-}$ are so high that the LSV technique and eqn. (13) had to be used for the determination of the rate constants. However, the rate constants determined are somewhat uncertain due to non-ideal behaviour; the peaks were too broad and the values of $-\mathrm{d}E_p/\mathrm{dlog}(v)$ too large compared to the theoretical values for a simple DISP1 mechanism. The non-ideal behaviour may be due to contribution from the rate of the heterogeneous electron transfer process but was not further investigated.

Measurements using $5^{\bullet-}$ as EGB. The kinetic data obtained using the thermodynamically very weak acid **1a**, $Ph_3P^+CH_3$, give an excellent fit to the working curve for the DISP1 mechanism, whereas the data obtained using **1b**, $Ph_3P^+CH_2CH_2CH_2CH_3$, for unknown reasons do not. The rate constant calculated for proton transfer from **1b** is therefore only an approximate value. The rate constant for proton transfer from **1c**, $Ph_3P^+CH_2Ph$, was obtained by an excellent fit to the theoretical data but surprisingly the value is close to that obtained for the thermodynamically much weaker (*cf.* Table 1) phosphonium ion **1a**, $Ph_3P^+CH_3$, (corrected for the different number of equivalent protons in the two compounds). This contrasts with the relative rate constants found for deprotonation of the same two compounds using $4^{\bullet-}$ as base where the rate constant found for **1c**, $Ph_3P^+CH_2Ph$, is approximately an order of magnitude larger than the rate constant determined for **1a**, $Ph_3P^+CH_3$. The azobenzene EGB $5^{\bullet-}$ is the only base used for which any reaction of **1d**, $Bu_3P^+CH_2Ph$, was detected, and the reaction is so slow that the rate constant is more uncertain than the others reported using this EGB. The most interesting feature is the fact that whereas the change from R = Ph to Bu in the pair, $R_3P^+CH_2CO_2Et$, **1g** and **1f**, gives rise to a change in the rate constant less than a factor of five, the change from R = Ph to Bu in the pair $R_3P^+CH_2Ph$, **1c** to **1d**, gives rise to a change in the rate constant of more than two orders of magnitude.

Rates of proton transfer and thermodynamic acidity

Relative kinetic acidities of the series of phosphonium cations. In order to be able to compare the kinetic acidities of the entire series of phosphonium cations on a single scale, it is necessary to 'overlap' the four series of kinetic data obtained using the four different EGBs. This, however, proved to be difficult. In an ideal situation the change from one EGB to another EGB with a different basicity would amount to a change by a constant factor of the measured rate constants for the same series of acids (HA_i), *i.e.* $k_{EGB2}(HA_i) = \text{constant} \times k_{EGB1}(HA_i)$—or using the logarithms of the rate constants: $\log[k_{EGB2}(HA_i)] = \log[k_{EGB1}(HA_i)] + \text{constant}$. The kinetic data in Table 3 do not follow this relationship: using as the basis of the comparison the values ($k_{4^{\bullet-}}$) obtained with phenazine **4** as probase, since this EGB is the one for which there are data for the largest number of phosphonium ions, the values of $\log[k_{EGB}(HA_i)]$ were plotted against $\log[k_{4^{\bullet-}}(HA_i)]$ for each of the three other EGBs. The results are shown in Fig. 3, and obviously we do not have three horizontal lines. Due to the limited amount of data for EGBs 2^{2-} and $5^{\bullet-}$ these points could be on two horizontal lines, but for the data relating to 3^{2-} this cannot be the case.

The apparent linear relationship between $\log[k_{3^{2-}}(HA_i)]$ and $\log[k_{4^{\bullet-}}(HA_i)]$ is intriguing. It means that the multiplier connecting rates of deprotonation of individual phosphonium cations is varying continuously from salt to salt when the EGBs $4^{\bullet-}$ and 3^{2-} are compared or, in other words, that the response

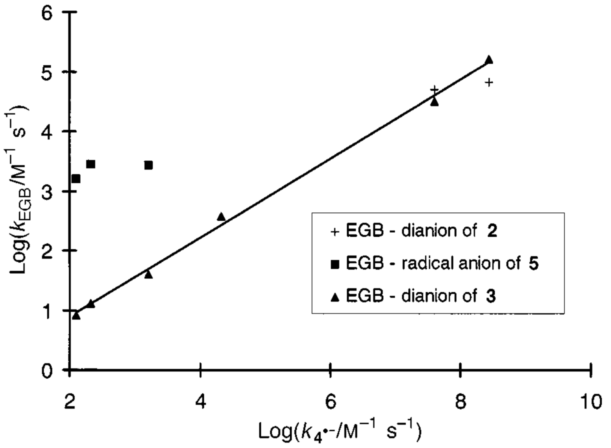

Fig. 3 Comparisons of rate data for different EGBs.—Data from Table 3.

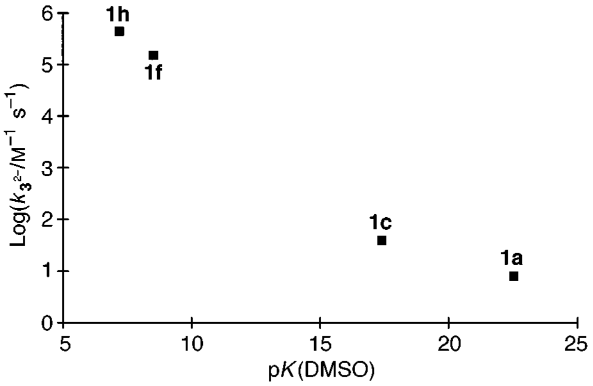

Fig. 4 Attempted Brønsted plot using EGB derived from **3**

factor for a change in the driving force for the proton transfer (normally the Brønsted α-value) is different for the two bases. As a consequence it is not possible with any confidence to use overlapping rate data from pairs of different probases to construct a meaningful table of relative rates of deprotonation. The possible origin of this difficulty is discussed in the following sections.

Using only the rate constants obtained using the dianion of **3**, and estimating from the plot in Fig. 3 an approximate rate constant for the reaction of **1a** with 3^{2-}, a Brønsted plot results in a non-linear relationship (Fig. 4). Since there was an apparent linear correlation between the data obtained using 3^{2-} and those obtained using $4^{\bullet-}$ a similar non-linear relationship will be obtained using the rate constants related to **4** in the Brønsted plot. This non-linearity is in contrast to what we have observed for the same type of EGBs when the proton donors were bissulfones of the type $RSO_2CH_2SO_2R$.[19] For a given EGB, acceptable Brønsted plots (log$k$ *vs.* pK) are obtained provided that sulfones likely to offer steric hindrance to proton transfer were excluded.[19] Linear relationships have also previously been obtained using the radical anions of azobenzene derivatives as EGBs for series of phenylacetonitriles and for series of benzylsulfones,[5] or the radical anion of anthracene for deprotonation of a series of phenols.[6] The possible origin of the non-linearity in the present case will also be discussed in the following sections.

Driving force for proton transfer. Unfortunately the thermodynamic basicity of the EGBs used is not known but the final products of hydrogenation of the probases are known; hydrogenation of the C–C double bond for **2** and **3**,[20] 9,10-dihydrophenazine for **4**[21] and 1,2-diphenylhydrazine for **5**.[22] The most basic site in 2^{2-} and 3^{2-} is expected to be C-9 rather than the exocyclic carbon atom, C-10. This is based on the *ca.* 10 pK unit difference in the thermodynamic acidity in DMSO

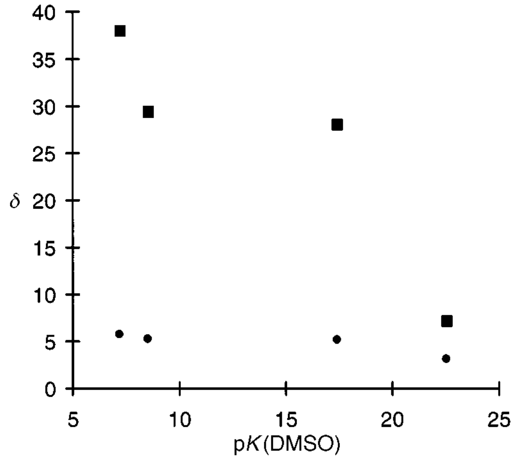

Fig. 5 ^{1}H (●) and ^{13}C (■) chemical shifts ($R_3P^+CH_2Y$), measured in [$^2H_6$]DMSO, plotted *vs.* p*K*(DMSO)[1]

between fluorene (p*K* = 22.6)[7] and $CH_2(CN)_2$ (p*K* = 11.1)[7] or $CH_2(CN)CO_2Et$ (p*K* = 13.1)[23] which argues strongly in favour of the C-9 position being the more basic. The 'extra' negative charge in $\mathbf{2}^{2-}$ and $\mathbf{3}^{2-}$ compared to the fluorenide anion is expected to increase the thermodynamic basicity of the dianions compared to the fluorenide anion, and consequently p*K*($\mathbf{2H}^-$) and p*K*($\mathbf{3H}^-$) are expected to be higher than 22.6. The p*K* of 9,10-dihydrophenazine ($\mathbf{4H_2}$) is not known in DMSO but the p*K* of 1,2-diphenylhydrazine ($\mathbf{5H_2}$) in DMSO is 26.2.[7] The thermodynamic acidity of the conjugate acids of the radical anions ($\mathbf{4H}^\bullet$) and ($\mathbf{5H}^\bullet$) are probably somewhat higher than the thermodynamic acidity of ($\mathbf{4H_2}$) and ($\mathbf{5H_2}$) in DMSO in analogy with the relative thermodynamic acidities of the conjugate acids of *e.g.* anthracene radical anion and the monoanion of 9,10-dihydroanthracene.[24] In conclusion, the thermodynamic basicity of the four applied EGBs may be very similar with p*K* values in the range 23–25 in DMSO.

These estimates of the thermodynamic basicities of the EGBs should be compared with the thermodynamic acidities of the studied phosphonium cations. The p*K* values in DMSO are known for four of them,[1] *cf.* Table 1, and an independent assessment of the polar effects at the methylene group in $R_3P^+CH_2Y$ may be obtained from the ^{1}H and ^{13}C chemical shifts which are known[25] to be significantly influenced by electron demand at the carbon atom. The relevant ^{1}H and ^{13}C chemical shifts have been measured for the phosphonium salts in [$^2H_6$]DMSO and both the ^{13}C and ^{1}H chemical shifts are consistent with the order of acidities known[1] for four of the phosphonium salts studied, although the relationship is qualitative (Fig. 5). Also the potentials of the first irreversible reduction of the triphenylphosphonium ions correlate quite well with both ^{1}H and ^{13}C chemical shifts and the results are displayed in Fig. 6. Superimposed on those plots are values for the two tributylphosphonium ions in the study which clearly form a very distinct set.

The estimated thermodynamic basicities of the EGBs and of the thermodynamic acidities of the phosphonium cations indicate that (with perhaps the exception of **1d**) all the proton transfer reactions studied should be thermodynamically favourable.

Role of the atom receiving the proton. The kinetic basicities of the two radical anions derived from **4** and **5** in which the site of protonation is definitely nitrogen, are much higher than those of the dianionic EGBs despite the similarities in thermodynamic basicity as estimated above. For the phosphonium salts, *e.g.* **1c**, **1e**, **1f** and **1g**, the rate constants for proton transfer to the radical anions of phenazine (**4**) or azobenzene (**5**) are 2–3 orders of magnitude greater than for proton transfer to the dianions of **2** or **3** which is almost certainly to carbon. This is not unexpected since protonation of carbanions analogously to deprotonation of carbon acids often are orders of magnitude slower than protonation of oxygen and nitrogen anions.[4]

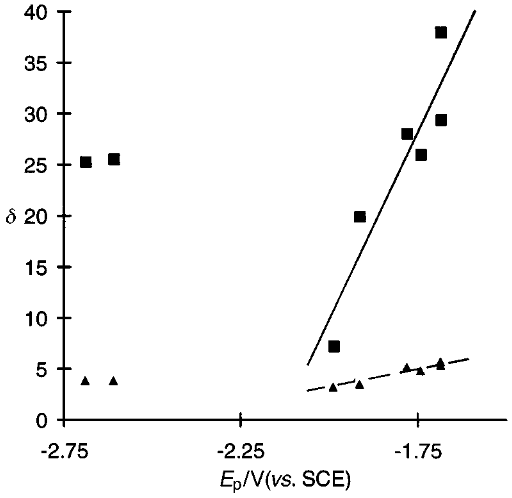

Fig. 6 ^{1}H (△) and ^{13}C (■) chemical shifts ($R_3P^+CH_2$), measured in [$^2H_6$]DMSO, plotted *vs.* the irreversible reduction potentials for ($R_3P^+CH_2$) (see Table 1)

Since the rates of proton transfer to the dianions are far from diffusion controlled, the coulombic attraction between the dianions and the cationic acids is not expected to have any influence on the rate of proton transfer. However, the (smaller) coulombic attraction between $\mathbf{4}^{\bullet-}$ or $\mathbf{5}^{\bullet-}$ and the most acidic phosphonium cations for which the measured rate constants are approaching the rate constant for a diffusion controlled process may contribute to the magnitude of the measured rate constant.

Role of the atom from which the proton is transferred—the role of enolisation. The difference between those phosphonium ions which are unambiguously carbon acids (compounds **1a**–**e**) and those which contain carbonyl groups α to the $-CH_2-$ group (compounds **1f**–**h**) is first of all a considerably higher thermodynamic acidity of the latter type (*cf.* the p*K* values for **1f** and **1h** in Table 1). This is also associated with a significant increase in proton transfer rate: for a given probase the latter group gives rates of proton transfer *ca.* 10^3 times faster than the first group which may not only be associated with the higher thermodynamic acidity but also with the enolisation of the phosphonium cation. Using ^{1}H NMR spectroscopy the phosphonium salt **1h** was shown to contain 14% enol at equilibrium in DMSO, whereas the equilibrium constant for enolisation of **1f** and **1g** is so small that the enol form is not detected by NMR spectroscopy, *i.e.* the enol content is <1%.

However, since the intrinsic rate constant for the oxygen based acid may be several orders of magnitude larger than the rate constant of the corresponding carbon acid,[4] the enhanced kinetic acidity of the enol-protons certainly contributes to the very high measured rate constant in the case of **1h** and may to an unknown extent contribute to the kinetic acidities measured for **1f** and **1g**. Some of the apparent upward curvature in the Brønsted plot in Fig. 4 (which includes **1f** and **1h**) may be related to this phenomenon.

Possible intervention of steric factors. The indications of electron demand at the methylene group of the phosphonium ions, taken from NMR chemical shifts, relate to initial state properties and are, to a first approximation, independent of steric factors. The same is true for the reduction potentials and for the thermodynamic acidity which is independent of the base involved. The kinetic results, on the other hand, are crucially influenced by both polar and steric factors which may emanate from either the EGB or the phosphonium salt as well as by the precise nature of the proton transfer reaction as discussed above.

Steric effects are probably responsible for the curious 'levelling' of rates of proton transfer to the radical anion of azobenzene $\mathbf{5}^{\bullet-}$ in the series **1a**–**c**. For both phenazine radical anion

4$^{\bullet-}$ and the dianion of **3** (accepting the values given by extrapolation) the rate of proton transfer from the benzylphosphonium ion **1c** is significantly greater than that from the alkylphosphonium salts **1a** and **1b**. This is entirely consistent with the known[1] greater acidity of **1c**. But this increase in rate is not found for the azobenzene derived EGB **5**$^{\bullet-}$ in which the negative charge, on the nitrogens, is hindered relative to the nitrogens in phenazine. Thus it is likely that the more hindered base **5**$^{\bullet-}$ reacts more slowly than expected with the more acidic but more hindered benzylic cation **1c** *vis à vis* the less acidic and less hindered ions **1b** and **1a**.

Bu_3P^+ *cf.* Ph_3P^+ substituent effect. The $Bu_3P^+CH_2Y$ and $Ph_3P^+CH_2Y$ ions clearly behave very differently in the proton transfer reactions but analysis of this difference is problematical. The relative reactivities depend on the type of cation (enolisable or not) and on the probase. The phosphonium ions **1f** and **1g** react at comparable rates with the EGB derived from **2** but the triphenylphosphonium cation reacts 5–7 times faster with EGBs from **3** and **4**. In contrast the triphenylphosphonium cation **1c** is about two orders of magnitude more reactive towards EGB **5**$^{\bullet-}$ than its tributyl counterpart **1d**. A possible explanation is that where enolisation is precluded, as in **1c** and **1d**, the triphenylphosphonium group is the more activating for proton transfer from the adjacent methylene group. Zhang and Bordwell[1] attribute the greater anion-stabilising effect of Ph_3P^+ *cf.* Me_3N^+ to a combination of inductive and polarisability effects; similarly Bu_3P^+ is less polarisable than Ph_3P^+. But for the enolisable salts **1f**, and **1g** the picture is complicated by possibilities for fast proton transfer from the enols, the contents of which may differ between the two series.

In the case of **1g** participation of the six equivalent protons in the butyl groups to the proton transfer can be ruled out on the basis of their expected acidity compared to the doubly activated $Bu_3P^+CH_2Y$ protons. In the case of **1d** participation of the butyl protons cannot be ruled out since for **1c**, $Ph_3P^+CH_2Ph$, and **1b**, $Ph_3P^+CH_2CH_2CH_2CH_3$, the difference in proton transfer rate is less than an order of magnitude for all applied EGBs but only a factor of 1.1 for **5**$^{\bullet-}$ which is the only EGB deprotonating **1d** on the timescale of the measurements.

Conclusions

Kinetic acidities of phosphonium cations defined as the second order rate constant for proton transfer to electrogenerated bases (EGBs) can conveniently be measured by electroanalytical techniques (derivative cyclic voltammetry or linear sweep voltammetry) in a very broad range of rate constants (6–7 orders of magnitude). Two structurally different types of electrogenerated bases with comparable thermodynamic basicities but with different kinetic basicities have been used to characterise the kinetic acidities of the series of phosphonium salts. Since some of the phosphonium cations are subject to enolisation a single Brønsted relationship (log$k$[proton transfer] *vs.* pK) does not hold for the series of phosphonium cations even for a single common EGB. In addition, for certain combinations of phosphonium cations and EGBs the proton transfer reaction appears to be subject to steric hindrance. Chemical shifts (^{13}C and ^{1}H) and reduction potentials of the phosphonium salts are, as measures of electron-demand, consistent with the few reported pK(DMSO) values. The kinetic results also confirm that the Ph_3P^+ group is, for non-enolisable phosphonium ions, more activating than Bu_3P^+.

Experimental

Chemicals

Probases. Phenazine (Fluka, *purum*) and azobenzene (Merck, *para sintesis*) were used as received. The dicyano(fluoren-9-ylidene)methane and 2-cyano-2-(fluoren-9-ylidene)ethyl acetate were synthesised by Knoevenagel condensation from fluorenone and, respectively, malononitrile and ethyl cyanoacetate using modifications of literature methods.[26]

Acids. The phosphonium salts, $Ph_3P^+CH_3$ Br^- (Aldrich) and $Ph_3P^+CH_2COMe$ Cl^- (Aldrich) were dried under vacuum before use. The phosphonium salts, $Ph_3P^+(CH_2)_3CH_3$ Cl^-, $Ph_3P^+CH_2CH{=}CHPh$ Cl^-, $Ph_3P^+CH_2Ph$ Br^- and $Ph_3P^+CH_2CO_2Et$ Br^- were prepared by reaction between triphenylphosphine and the corresponding halides.[27] The phosphonium salts $Bu_3P^+CH_2Ph$, Cl^- and $Bu_3P^+CH_2CO_2Et$ Br^- were prepared by reaction between tributylphosphine and the corresponding halides.[27]

Solvents and electrolytes. The solutions of tetrabutylammonium hexafluorophosphate (0.1 M) in dimethyl sulfoxide (Fluka, *puriss.*) were passed through a column filled with neutral alumina (Woelm, W200) before the measurements were made. [$^2H_6$]DMSO (Fluka, *puriss.*) solutions of phosphonium salts were used to record ^1H and ^{13}C NMR spectra.

Electrodes, cells and instrumentation. For the kinetic measurements, the electrodes, cells and the electrochemical instrumentation, as well as the measurement and data handling procedures for derivative cyclic voltammetry and linear sweep voltammetry were identical to those previously described.[28]

NMR spectroscopy. The NMR spectra were recorded on a Varian Unity Plus spectrometer. Both ^1H NMR (300 MHz) and ^{13}C NMR (75 MHz) spectra used the solvent peak as an internal reference.

Digital simulations. The theoretical DCV response for the DISP1 mechanism, Scheme 3, the simple EC mechanism (method 2) and the full EEC mechanism in Scheme 2 (method 1) was obtained by digital simulation using the fully implicit method described by Rudolph[29] using locally developed software as described elsewhere.[30] For the EEC mechanism two different sets of theoretical data were generated, one using $E^o(1) - E^o(2) = 0.72$ V corresponding to probase **2**, and one using $E^o(1) - E^o(2) = 0.52$ V corresponding to probase **3**.

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