

# The $S_{RN}1$ Reaction: An Attempt to Calculate the Thermodynamic Driving Force for the Addition of Nucleophiles to Phenyl Radical

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**Dedicated to Professor Lennart Ebersson on the occasion of his 65th birthday**

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Phenyl radical is formed in the propagation chain of the aromatic  $S_{RN}1$  reaction from cleavage of the radical anion of the precursor phenyl halide ( $PhX^{\cdot-}$ ); subsequent addition of nucleophile  $Y^-$  to  $Ph^{\cdot}$  yields the radical anion of the substitution product ( $PhY^{\cdot-}$ ). In this addition step, transfer of an electron from the nucleophile to  $Ph^{\cdot}$  is concerted with bond formation, and the extra electron of the new two-center three-electron bond is, in general, located in a  $\pi^*$  MO of the aromatic moiety. Three factors mainly affect the efficiency of this addition step: (i) the energy of the new Ph–Y bond; (ii) the stability of the radical anion of the substitution product; (iii) the oxidation potential of the nucleophile. In keeping with these points, the energy of some Ph–Y bonds has been calculated, and the oxidation potential of  $Y^-$  species, along with the reduction potential of the related PhY substitution products, have been determined. Calculation of the thermodynamic driving force of the nucleophile/radical addition step is reported for some significant nucleophiles. Finally, comparison of the thermodynamic driving force with experimental reactivity of the same nucleophile in the addition step is attempted.

Electron transfer steps sometimes play a key role in organic systems.<sup>1</sup> This happens to be the case for aromatic nucleophilic substitution reactions which proceed through the  $S_{RN}1$  mechanism.<sup>2</sup> Subsequent to the injection of electrons into the substrate (e.g., PhX), the radical anion  $PhX^{\cdot-}$  is formed, eqn. (1); it releases halide ion, giving rise to a phenyl  $\sigma$ -radical ( $Ph^{\cdot}$ ) as a reactive intermediate, eqn. (2).



Electrons can be supplied to the substrate by dissolving metals in liquid ammonia,<sup>2</sup> or from an electrode.<sup>3</sup> Electrochemical investigation has demonstrated the intermediacy of  $PhX^{\cdot-}$  as a short-lived species in  $S_{RN}1$  processes.<sup>4</sup> This is due to the fact that a  $\pi^*$  MO, which initially accommodates the incoming electron, is available to the aryl halide.<sup>5</sup> The electron is subsequently transferred intramolecularly from the  $\pi^*$  to the  $\sigma^*$  MO of the C–X bond, causing cleavage of that bond [ $k_{cl}$  in eqn. (2)].

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Electrochemical studies have provided  $k_{cl}$  values for a fairly large number of aryl halides.<sup>6</sup>

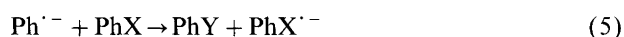
Aryl radicals are efficient H-atom scavengers, and abstraction of a hydrogen atom from the solvent may ensue, eqn. (3).<sup>7</sup>



However, an outcome more synthetically alluring than this electron-induced dehalogenation process derives from addition of a nucleophile  $Y^-$  to phenyl radical, eqn. (4): this leads to the formation of a new radical anion intermediate.<sup>2</sup>



Subsequent electron transfer from the  $PhY^{\cdot-}$  species to PhX, eqn. (5), leads to the substitution product of the  $S_{RN}1$  reaction and to  $PhX^{\cdot-}$ , which re-enters the propagation cycle at the level of eqn. (2).



In this paper we investigate the features on which the reactivity of the nucleophile in an  $S_{RN}1$  reaction is grounded and, in particular, focus on the step of addition of  $Y^-$  to the intermediate radical, eqn. (4). Facets of the

mechanism of this step have already been elucidated by Savéant.<sup>5,8</sup> First of all, when a new  $\sigma$  bond begins to form between the  $sp^2$  carbon-centered radical ( $\text{Ph}^\cdot$ ) and  $\text{Y}^-$ , in what is going to be a two-center, three-electron bond, the odd electron is at first located in the low energy  $\sigma^*$  MO of the partially formed C–Y bond. As this new bond shortens, gradually approaching the normal C–Y bond length, the energy of its  $\sigma^*$  MO increases, reaching a point where it may match the energy of a  $\pi^*$  MO of the molecule: transfer of the electron from the  $\sigma^*$  (which will then continue to rise somewhat in energy) to this  $\pi^*$  MO occurs, as Fig. 1 naively illustrates.<sup>9</sup>

As a consequence, formation of an  $\text{S}_{\text{RN}}1$  substitution product should be easier the lower the energy of an available  $\pi^*$  MO.<sup>5,8–12</sup> Secondly, since a new bond is formed in this step, it is reasonable that the stronger the bond the easier will be the addition itself. Finally, addition step (4) is viewed as an inner-sphere ET, as formation of the new bond is concerted with transfer of the electron from the nucleophile to phenyl radical;<sup>5,8</sup> therefore, good electron-donor character of  $\text{Y}^-$  is expected to increase the efficiency of step (4).

In keeping with the above description, and following preceding publications,<sup>10</sup> determination of pertinent thermodynamic and electrochemical parameters has been attempted here, in order to permit a survey of the roots of  $\text{S}_{\text{RN}}1$  reactivity for a wide range of  $\text{Y}^-$  species.

## Results and discussion

*Thermodynamic driving force of the nucleophile/radical addition.* Savéant has suggested a way of calculating the thermodynamic driving force for the addition of nucleophiles to an aryl radical, which can be defined as the free energy of formation of the radical anion of the substitution product ( $\Delta G^\circ$  for  $\text{Ar}^\cdot + \text{Y}^- \rightarrow \text{ArY}^{\cdot-}$ ) and has the same form as that related to the reverse reaction, that is the cleavage of a radical anion ( $\text{ArY}^{\cdot-} \rightarrow \text{Ar}^\cdot + \text{Y}^-$ ).<sup>5,8,13</sup> In keeping with the points delineated in the Introduction and described in Fig. 1, the proposed equation, eqn. (6), requires knowledge of (i) the standard potential for reduction of the substitution product  $\text{PhY}$  (i.e.,  $E_{\text{PhY}/\text{PhY}^{\cdot-}}^\circ$ ), which is an indirect measure of the energy of the  $\pi^*$  MO orbital, (ii) the standard oxidation potential of the nucleophile (i.e.,  $E_{\text{Y}^-/\text{Y}^\cdot}^\circ$ ), and (iii) the strength of the bond being formed, expressed as the free energy

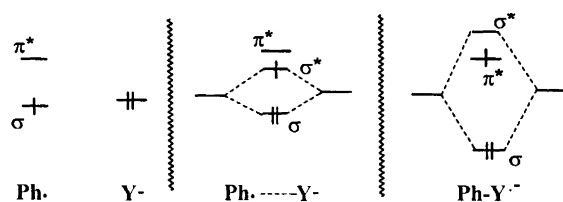


Fig. 1. Dynamic description of the nucleophile/phenyl radical addition step in terms of energy change of the relevant MOs.

of formation of the new bond (i.e.,  $\Delta G_{\text{PhY}}^\circ$ ).

$$\Delta G_{\text{PhY}^{\cdot-}}^\circ = -FE_{\text{PhY}/\text{PhY}^{\cdot-}}^\circ + FE_{\text{Y}^-/\text{Y}^\cdot}^\circ - \Delta G_{\text{PhY}}^\circ \quad (6)$$

Several drawbacks limit the use of this equation. Standard  $E^\circ$  values are needed, while in most cases irreversible  $E^p$  potentials are instead experimentally accessible. Then, there is a dramatic shortage of thermochemical data concerning the formation of Ph–Y bonds. It appeared useful to gather these electrochemical and thermochemical data, in order to be able to verify the predictions of eqn. (6).

*Oxidation potential of the  $\text{Y}^-$  anion.* Generally speaking, standard oxidation potentials of  $\text{Y}^-$  species are difficult to measure by conventional electrochemical methods, because the determination may be hampered by follow-up reaction(s) of the oxidized species (i.e.,  $\text{Y}^\cdot$ ), which makes the cyclic voltammetry (CV) wave irreversible.<sup>14</sup> A few  $E^\circ$  values are quoted,<sup>1</sup> while others have been calculated from thermochemical cycles by making use of gas-phase data, and the resulting values transferred to aqueous solution or to other solvents.<sup>5,8,15</sup> Our previous reactivity studies of the  $\text{S}_{\text{RN}}1$  reaction were carried out on  $\text{Me}_2\text{SO}$  solutions;<sup>10,16</sup> for consistency, determination of the oxidation potential of nucleophiles was first sought in this solvent by CV techniques. Only irreversible oxidation waves were obtained, however. Lack of stability of some nucleophiles in this solvent also gave problems of reproducibility of the measurements, which were only in part solved on occasionally changing the supporting electrolyte from  $\text{Bu}_4\text{NBF}_4$  (i.e., TBAF) to  $\text{LiClO}_4$ . The  $E^p$  values (Table 1) were obtained at a sweep scan of  $500 \text{ mV s}^{-1}$ ; these represent the most reliable determinations we were able to get despite the problems of reproducibility hinted at before. Determination of the  $E^p$  values was also attempted for solutions in MeCN, which provided better reproducibility than  $\text{Me}_2\text{SO}$ . In the case of a few  $\text{Y}^-$  ions, even  $E^\circ$  values could be attained by following the CV approach described by Savéant (Table 1; see Experimental).<sup>14</sup> Savéant had obtained 0.1 V (vs. SCE) as the  $E^\circ$  of  $\text{PhS}^-$  in MeCN by the use of appropriate scan rates. Our determination, i.e., 0.096 V vs. SCE, is in excellent agreement with his value.<sup>14</sup> By a similar approach, we determined  $E^\circ = 0.22 \text{ V}$  vs. SCE for  $\text{PhO}^-$  in MeCN, which is in line with the 0.24 V value previously extrapolated.<sup>17</sup> Table 1 collects also some other  $E^\circ$  values of the literature.<sup>5,18</sup>

*Reduction potential of substitution product  $\text{PhY}$ .* Access to  $E_{\text{PhY}/\text{PhY}^{\cdot-}}^{\text{red}}$  values by CV was also sought. These were carried out in THF (vs. SCE), rather than in  $\text{Me}_2\text{SO}$ , in order to avoid the problems associated with undue deprotonation of the substrates by the strongly basic radical anions generated in the medium.<sup>19</sup> The results are reported in Table 1. Unfortunately, in most cases the reduction wave did not appear before the discharge of the supporting electrolyte (i.e.,  $\leq -2.9 \text{ V}$ , in TBAF), so

**Table 1.** Oxidation potentials of nucleophiles Y<sup>-</sup> in Me<sub>2</sub>SO at 25 °C, and reduction potentials of substitution products PhY in THF at 25 °C, from cyclic voltammetry determinations.

| Nucleophile Y <sup>-</sup>                        | Entry no. | $E_{Y^{\bullet}/Y^-}^{\circ}$ (this work) <sup>a</sup> | $E_{Y^{\bullet}/Y^-}/V$ vs. SCE          | $E_{PhY/PhY^{\bullet}}^{\circ}$ (this work) <sup>a,b</sup> |
|---|-----------|--|--|--|
| CN <sup>-</sup>                                   | 1         | —  | 1.8 in DMF <sup>c,d</sup>                | -2.0 in DMF <sup>c</sup>                                   |
| (CH <sub>3</sub> CO) <sub>2</sub> CH <sup>-</sup> | 2         | —  | 1.0 in Me <sub>2</sub> SO <sup>d</sup>   | —  |
| (EtO) <sub>2</sub> PO <sup>-</sup>                | 3         | 0.34   | ca. 0.7 <sup>d</sup>                     | -2.57  |
| PhO <sup>-</sup>                                  | 4         | 0.25 in MeCN   | 0.24 in MeCN <sup>e</sup>                | ≤ -2.9 <sup>f</sup>  |
| Indenide <sup>-</sup>                             | 5         | -0.39  | -0.49 in Me <sub>2</sub> SO <sup>d</sup> | -2.5 <sup>g</sup>  |
| Fluorenyl <sup>-</sup>                            | 6         | -0.55 <sup>h</sup>                                     | -0.27 in Me <sub>2</sub> SO <sup>i</sup> | -2.6   |
| PhCOCH <sub>2</sub> <sup>-</sup>                  | 7         | -0.097 <sup>h</sup>                                    | —  | -1.88  |
| (2-Naphthyl)COCH <sub>2</sub> <sup>-</sup>        | 8         | -0.12  | —  | -1.74  |
| Cyclohexanone <sup>-</sup>                        | 9         | -0.20  | —  | ca. -3   |
| EtCOCHCH <sub>3</sub> <sup>-</sup>                | 10        | -0.15  | —  | ca. -3   |
| Me <sub>3</sub> CCOCH <sub>2</sub> <sup>-</sup>   | 11        | -0.15  | —  | ca. -3   |
| CH <sub>3</sub> COCH <sub>2</sub> <sup>-</sup>    | 12        | -0.04  | 0.49 in NH <sub>3</sub> <sup>j</sup>     | ca. -3   |
| PhS <sup>-</sup>                                  | 13        | 0.04   | 0.1 in MeCN <sup>k</sup>                 | ≤ -2.7 <sup>f</sup>  |
| NH <sub>2</sub> <sup>-</sup>                      | 14        | —  | 0.02 in NH <sub>3</sub> <sup>j</sup>     | ca. -3   |
| NO <sub>2</sub> <sup>-</sup>                      | 15        | —  | 0.7 in DMF <sup>c</sup>                  | -0.84 <sup>c</sup>   |
| Br <sup>-</sup>                                   | 16        | —  | 1.5 in DMF <sup>c</sup>                  | -2.20 <sup>c</sup>   |

<sup>a</sup>In V vs. SCE, at a 500 mV s<sup>-1</sup> sweep scan. <sup>b</sup>The structure of PhY is that resulting from phenylation at the formal site of the negative charge of Y<sup>-</sup>. <sup>c</sup>From Ref. 30. <sup>d</sup>From Ref. 1. <sup>e</sup>From Ref. 17; we obtain  $E^{\circ}$  of 0.22 V (see Experimental). <sup>f</sup>From Ref. 28. <sup>g</sup>Obtained as 3-phenylindene [see Ref. (10b)]. <sup>h</sup>Determined at 1 V s<sup>-1</sup> in MeCN. <sup>i</sup>From Ref. 41, vs. NHE (0.24 V is the conversion factor). <sup>j</sup>From Ref. 8, vs. 0.01 M Ag<sup>+</sup>/Ag. <sup>k</sup>From Ref. 14; we obtain 0.096 V.

the possibility of differentiating the  $E_{PhY/PhY^{\bullet}}^{\circ}$  value of these substrates is often prevented. In a previous paper<sup>10b</sup> we tried to circumvent this levelling effect of the medium by making calculations of the LUMO energy of the substitution product. In this way we were able to discriminate, at least qualitatively, varying degrees of electron affinity among PhY species.

**The energy of the C–Y bonds.** In order to determine the contribution of  $\Delta G_{Ph-Y}^{\circ}$  to the driving force of the S<sub>RN</sub>1 reaction, as required by eqn. (6), knowledge of the bond dissociation energy (BDE) of the new bond is needed.<sup>13a,b</sup> The BDE<sub>Ph-Y</sub> is an enthalpic term, and it must be corrected for the entropic change, as in eqn. (7), in order to obtain the free energy  $\Delta G_{Ph-Y}^{\circ}$  term of eqn. (6).

$$\Delta G_{Ph-Y}^{\circ} = BDE_{Ph-Y} - T\Delta S_{react}^{\circ} \quad (7)$$

The entropy change of the addition reaction (i.e.,  $\Delta S_{react}^{\circ}$ ) was calculated according to eqn. (8). Available entropy values for radical and neutral species of interest were used.<sup>20,21</sup> Whenever these values were not available, the entropy of the structurally closest compound was taken, or it was calculated through Benson's approach (Table 2).<sup>21,22</sup> The entropy calculated by Benson's group increments<sup>22</sup> was corrected for the overall rotational symmetry of the molecule (see the Appendix).

$$\Delta S_{react}^{\circ} = S^{\circ}(Ph-Y) - S^{\circ}(Ph^{\bullet}) - S^{\circ}(Y^{\bullet}) \quad (8)$$

Access to BDE data relies in general on the use of relationships such as that of eqn. (9),<sup>23</sup> where gas-phase enthalpies of formation of radicals and neutral species are employed.<sup>24</sup>

$$BDE_{Ph-Y} = \Delta_f H_{298}(Ph^{\bullet}) + \Delta_f H_{298}(Y^{\bullet}) - \Delta_f H_{298}(Ph-Y) \quad (9)$$

A recent<sup>25</sup> redetermination of  $\Delta_f H_{298}(Ph^{\bullet})$  (i.e., 81.1 kcal mol<sup>-1</sup>) is ca. 2.5 kcal mol<sup>-1</sup> higher than the previously accepted enthalpy of formation of phenyl radical, and compels one to recalculate all the BDE values that were derived from the previous value.<sup>24</sup> By exploiting the new  $\Delta_f H_{298}(Ph^{\bullet})$  value<sup>25</sup> and eqn. (9), the BDE of many Ph–Y bonds was determined (Table 3). Calculation of the  $\Delta_f H_{298}(PhY)$  term was needed in some cases, due to lack of direct experimental data,<sup>24</sup> and it was achieved by use of Benson's group increments.<sup>22</sup> Cases where the experimental  $\Delta_f H_{298}(PhY)$  value was directly available allow one to appreciate the very high confidence that can be given to Benson's method, on comparing the experimental with the calculated values of  $\Delta_f H_{298}(PhY)$ .

Use of eqn. (7) gave the desired  $\Delta G_{Ph-Y}^{\circ}$  terms (Table 4). Since bond energies are not much affected by solvation, calculation of the  $\Delta G_{Ph-Y}^{\circ}$  values of Table 4 from gas-phase thermochemical data, even for a study of reactivity in solution, is justified.<sup>26</sup>

Finally, evaluation of the thermodynamic driving force of step (4) was attempted by means of eqn. (6). An evaluation of the error affecting the  $\Delta G_{Ph-Y}^{\circ}$  values is not easy. For example, it depends on the precision with which the enthalpic and entropic terms are known (Tables 2 and 3). Depending on the cases, an uncertainty varying from ±0.5 to ±2 kcal mol<sup>-1</sup> could be given. It is also fair to admit that the  $\Delta G_{PhY^{\bullet}}^{\circ}$  values are certainly affected by the approximations with which some of the redox potentials of Table 1 are known. However, on looking at the contributions of the three terms of eqn. (6) (in Table 4), it emerges that, in most cases, the major input to the thermodynamic driving force of the addition step arises from the  $\Delta G_{Ph-Y}^{\circ}$  term. Hence, even substantial

Table 2. Calculation of the entropic contribution to Ph-Y bond formation at 298 K.

| Y <sup>•</sup>                                    | S <sub>(Y<sup>•</sup>)</sub> /cal mol <sup>-1</sup> K <sup>-1 a,b</sup> | S <sub>(Ph-Y)</sub> /cal mol <sup>-1</sup> K <sup>-1</sup> | ΔS <sub>react</sub> <sup>o</sup> /cal mol <sup>-1</sup> K <sup>-1 c</sup> | TΔS <sub>react</sub> <sup>o</sup> /kcal mol <sup>-1</sup> |
|---|---|--|---|---|
| CH <sub>3</sub> COCH <sub>2</sub> <sup>•</sup>    | 71.5  | [101]  | -40   | -12   |
| Br <sup>•</sup>                                   | 41.8  | 77.5   | -33.7   | -10.0   |
| CN <sup>•</sup>                                   | 48.4  | 76.7   | -41.1   | -12.2   |
| NH <sub>2</sub> <sup>•</sup>                      | 46.5  | 76.3   | -39.6   | -11.8   |
| PhS <sup>•</sup>                                  | 76.5  | [103]  | -43   | -13   |
| PhCOCH <sub>2</sub> <sup>•</sup>                  | 89 (acetophenone)   | [123]  | -35   | -10   |
| PhO <sup>•</sup>                                  | 73.7  | [99]   | -44   | -13   |
| Cyclohexanone <sup>•</sup>                        | 76 (cyclohexyl <sup>•</sup> )   | 94 (biphenyl)  | -51   | -15   |
| Indenyl <sup>•</sup>                              | 80 (indene)   | 94 (biphenyl)  | -55   | -17   |
| (CH <sub>3</sub> CO) <sub>2</sub> CH <sup>•</sup> | [80 (acetylacetone)]  | [121]  | -28   | -8  |
| NO <sub>2</sub> <sup>•</sup>                      | 57.5  | 78   | -49   | -15   |

<sup>a</sup>From Refs. 20 or 21. <sup>b</sup>Values in brackets were calculated from Benson's additivity rules. <sup>c</sup>From eqn. (8), by taking S<sup>o</sup>(Ph<sup>•</sup>) as 69.4 cal mol<sup>-1</sup> K<sup>-1</sup>.<sup>21</sup>

Table 3. Enthalpy of formation of radicals and neutrals of interest; calculated BDE values of Ph-Y species.<sup>a</sup>

| Y <sup>•</sup>                                    | Δ <sub>f</sub> H <sub>298</sub> (Y <sup>•</sup> ) <sup>b</sup> | Δ <sub>f</sub> H <sub>298</sub> (PhY) <sup>b,c</sup> | BDE <sub>Ph-Y</sub> <sup>d</sup> |
|---|--|--|----------------------------------|
| CN <sup>•</sup>                                   | 104  | 51.6 [52.3]  | 134                              |
| PhO <sup>•</sup>                                  | 11.4   | 12.4 [10.2]  | 80.1                             |
| Indenyl <sup>•</sup>                              | 70.9 <sup>e</sup>  | [64]   | 88                               |
| Fluorenyl <sup>•</sup>                            | —  | —  | ca. 85 <sup>f</sup>              |
| NH <sub>2</sub> <sup>•</sup>                      | 44.3   | 20.8 [20.8]  | 105                              |
| PhS <sup>•</sup>                                  | 54.9   | 55.3 [55.3]  | 80.7                             |
| CH <sub>3</sub> COCH <sub>2</sub> <sup>•</sup>    | -5.7   | -23.6 [-23.9]  | 99                               |
| PhCOCH <sub>2</sub> <sup>•</sup>                  | 20.2 <sup>f,g</sup>  | 5.3 [5.6]  | 96                               |
| (CH <sub>3</sub> CO) <sub>2</sub> CH <sup>•</sup> | -50.9 <sup>h</sup>   | [-62]  | 92                               |
| α-( <sup>•</sup> )Cyclohexanone                   | -18 <sup>i</sup>   | [-26.8]  | 90                               |
| (EtO) <sub>2</sub> PO <sup>•</sup>                | [-169]   | [-200]   | 112                              |
| Br <sup>•</sup>                                   | 26.7   | 25.2   | 82.6                             |
| NO <sub>2</sub> <sup>•</sup>                      | 8.1  | 16.0   | 73                               |

<sup>a</sup>All data are in kcal mol<sup>-1</sup>. <sup>b</sup>From Ref. 24. <sup>c</sup>Values in brackets were calculated according to Benson's additivity rules.<sup>22</sup> <sup>d</sup>From eqn. (9), by taking Δ<sub>f</sub>H<sub>298</sub>(Ph<sup>•</sup>) = 81.1 kcal mol<sup>-1</sup> (see the text).<sup>25</sup> <sup>e</sup>Calculated from a BDE<sub>C-H</sub> of 84 kcal mol<sup>-1</sup> for indene. <sup>f</sup>See the Appendix. <sup>g</sup>Calculated from a BDE<sub>C-H</sub> of 93 kcal mol<sup>-1</sup> for acetophenone. <sup>h</sup>Calculated from a BDE<sub>C-H</sub> of 92 kcal mol<sup>-1</sup> for acetylacetone. <sup>i</sup>Calculated from a BDE<sub>C-H</sub> of 88 kcal mol<sup>-1</sup> for cyclohexanone.

Table 4. Thermodynamic driving force for the addition of nucleophiles to phenyl radical, eqn. (6). Also included are relative (*k*<sub>rel</sub>) and absolute (*k*<sub>abs</sub>) reactivities of the nucleophiles in the same step.

| Y <sup>a</sup> | BDE <sub>Ph-Y</sub> <sup>•</sup> /kcal mol <sup>-1</sup> | TΔS <sub>react</sub> <sup>o</sup> /kcal mol <sup>-1</sup> | ΔG <sub>Ph-Y</sub> <sup>o</sup> /kcal mol <sup>-1 b</sup> | F(E <sub>Y</sub> <sup>•</sup> /Y <sup>-</sup> )/kcal mol <sup>-1</sup> | F(E <sub>PhY/PhY<sup>•</sup>-)/kcal mol<sup>-1</sup></sub> | ΔG <sub>PhY<sup>•</sup>-</sub> <sup>o</sup> /kcal mol <sup>-1 c</sup> | <i>k</i> <sub>rel</sub> <sup>d</sup> | <i>k</i> <sub>abs</sub> /M <sup>-1</sup> s <sup>-1 e</sup> |
|----------------|--|---|---|--|--|---|--------------------------------------|--|
| 1              | 134  | -12.2   | 122   | 41.5   | -46  | -34   | 0                                    | <sup>g</sup>   |
| 2              | 92   | -8  | 84  | 23   | —  | —   | 0                                    |  |
| 3              | 112  | ca. -13 <sup>f</sup>                                      | (99)  | ca. 12   | -59  | ca. -28   | 2.2                                  | 4 × 10 <sup>8</sup>  |
| 4              | 80.1   | -13   | 67  | 5.1  | ≤ -67  | ca. 5   | 0                                    |  |
| 6              | ca. 85   | -17   | (68)  | -13  | -60  | ca. -21   | 4.3                                  | 9 × 10 <sup>8</sup>  |
| 7              | 96   | -10   | 86  | ca. -0.23  | -43  | ca. -43   | 3.6                                  | 7 × 10 <sup>8</sup>  |
| 8              | 96   | -10   | 86  | ca. -2.3   | -40  | ca. -48   | 4.2                                  | 8 × 10 <sup>8</sup>  |
| 9              | 90   | -15   | 75  | ca. -4.2   | ≤ -69  | ca. -10   | 0.5                                  | 1 × 10 <sup>8</sup>  |
| 10             | 99   | -12   | 87  | ca. -3   | ≤ -69  | ca. -21   | 1.5                                  | 3 × 10 <sup>8</sup>  |
| 11             | 99   | -12   | 87  | ca. -3   | ≤ -69  | ca. -21   | 1.0                                  | 2 × 10 <sup>8</sup>  |
| 12             | 99   | -12   | 87  | ca. -1   | ≤ -69  | ca. -19   | 1.1                                  | 2 × 10 <sup>8</sup>  |
| 13             | 80.7   | -13   | 68  | 2.3  | ca. -62  | ca. -4  | 0.4                                  | 8 × 10 <sup>7</sup>  |
| 14             | 105  | -11.8   | 93  | ca. -12  | ≤ -69  | ca. -36   | 2.1 <sup>h</sup>                     | 4 × 10 <sup>8</sup>  |
| 15             | 73   | -15   | 58  | 16   | -19  | -23   | 0.8                                  | 2 × 10 <sup>8</sup>  |
| 16             | 82.6   | -10.0   | 72.6  | 34.6   | -51  | 13  |                                      |  |

<sup>a</sup>Reference no. of the anions as in Table 1. <sup>b</sup>From eqn. (7). <sup>c</sup>From eqn. (6). <sup>d</sup>From competition experiments: see the text. <sup>e</sup>Determined from the *k*<sub>rel</sub> value, on the basis of the known rate of addition of PhS<sup>-</sup> (13) to Ph<sup>•</sup> (8 × 10<sup>7</sup> M<sup>-1</sup> s<sup>-1</sup> from Ref. 31): see the text. <sup>f</sup>Approximate value, taken as an average of the other TΔS<sup>o</sup> values listed (see the Appendix). <sup>g</sup>Ref. 27 estimates the reactivity of this anion toward Ph<sup>•</sup> as < 10<sup>8</sup> M<sup>-1</sup> s<sup>-1</sup>. <sup>h</sup>From Ref. 2(b).

uncertainties in the electrochemical terms of eqn. (6) (i.e.,  $FE_{\text{PhY}^{\bullet}/\text{PhY}^{\bullet-}}$  or  $FE_{\text{Y}^{\bullet}/\text{Y}^{\bullet-}}$ ) are not bound to affect dramatically the  $\Delta G_{\text{PhY}^{\bullet-}}^{\circ}$  value. Comment on a few significant cases allows one better to appreciate the subtleties on which the  $S_{\text{RN}}1$  reactivity of nucleophiles may be grounded.

*Case study.* The case of the enolate ion from a ketone is examined first, taking acetone enolate ion as an example (Scheme 1). This is a typical well-behaved nucleophile in  $S_{\text{RN}}1$  reactions,<sup>2</sup> good yields of the substitution product always being observed with a variety of aryl halides. For use in eqn. (6), an  $E^{\circ}$  of  $-0.04$  V for the oxidation potential of  $\text{CH}_3\text{COCH}_2^-$  is taken, with a  $\Delta G^{\circ}$  bond energy ( $\text{Ph}-\text{CH}_2\text{COCH}_3$ ) of  $87$  kcal mol<sup>-1</sup>, and the  $E_{\text{PhY}^{\bullet}/\text{PhY}^{\bullet-}}^{\circ}$  tentatively set at  $-3$  V. A thermodynamic driving force of  $-19$  kcal mol<sup>-1</sup> for the  $\text{Ph}^{\bullet} + \text{CH}_3\text{COCH}_2^- \rightarrow \text{PhCH}_2\text{COCH}_3^-$  addition can accordingly be determined. A previous estimate for this driving force was  $-10$  kcal mol<sup>-1</sup>.<sup>8</sup> Wide as the uncertainty on this  $\Delta G_{\text{PhY}^{\bullet-}}^{\circ}$  value may be, which could be improved if a better evaluation of the  $E_{\text{PhY}^{\bullet}/\text{PhY}^{\bullet-}}^{\circ}$  term were experimentally accessible, it can be appreciated that the addition step, eqn. (4), of this nucleophile is thermodynamically favoured. Such a favourable addition step is reasonably shared by the enolate ions of other ketones, and is consonant with the high rate constant reported for the addition of acetone enolate ion to phenyl radical (i.e.,  $3 \times 10^8$  M<sup>-1</sup> s<sup>-1</sup> at  $-33$  °C).<sup>6,13c,27</sup>

The case of  $\text{PhS}^-$  is examined next. From a  $\text{Ph}-\text{SPh}$  bond energy of  $68$  kcal mol<sup>-1</sup>, the above mentioned  $E_{\text{PhS}^{\bullet}/\text{PhS}^{\bullet-}}^{\circ}$  value of  $0.1$  V, and a  $E_{\text{PhY}^{\bullet}/\text{PhY}^{\bullet-}}^{\circ}$  value of  $-2.7$  V,<sup>28</sup> the thermodynamic driving force for addition of  $\text{PhS}^-$  to  $\text{Ph}^{\bullet}$  turns out to be  $-3.7$  kcal mol<sup>-1</sup>. This compares with a previously evaluated value of  $3.7$  kcal mol<sup>-1</sup>.<sup>8</sup> Whatever the approximation of this

value is, it appears that addition of  $\text{PhS}^-$  to  $\text{Ph}^{\bullet}$  is less favoured than that of the enolate ion; this result confirms an experimental reactivity finding ( $3 \times 10^7$  M<sup>-1</sup> s<sup>-1</sup> at  $-33$  °C, *vide infra*).<sup>27</sup>

Oxygen nucleophiles are, in general, unsuited to the  $S_{\text{RN}}1$  route.<sup>2</sup> The  $E_{\text{Y}^{\bullet}/\text{Y}^{\bullet-}}^{\circ}$  of  $0.22$  V for  $\text{PhO}^-$  confirms that this anion is a slightly worse electron donor than are the enolate ions. We find a  $\text{Ph}-\text{OPh}$  bond energy of  $67$  kcal mol<sup>-1</sup>, and the reduction potential for  $\text{PhOPh}$  can be estimated as  $-2.9$  V.<sup>28</sup> A thermodynamic driving force of ca.  $5$  kcal mol<sup>-1</sup> can thus be evaluated for  $\text{PhO}^-$  ion. The endoergonicity of the addition step endorses the unreactivity of this oxygen nucleophile in the  $S_{\text{RN}}1$  reaction. It is also in keeping with the fact that bidentate nucleophiles, such as the enolate ions, give only C-C coupling and not C-O coupling with aryl radicals, thus behaving exclusively as carbon-nucleophiles.<sup>2,5,10</sup>

Halide ions are examined next. Halide ions are always present in the reaction medium of an  $S_{\text{RN}}1$  process, because they are the most common leaving groups produced from fragmentation of the radical anion of the substrate [step (2)]. Nevertheless, no evidence for 'return' of the halide, nor for combination of any other halide ion purposely added in the medium, to the intermediate radical has ever been reported, eqn. (10).<sup>2,29</sup>



Lack of occurrence of step (10), i.e., the reverse of step (2), can be explained on thermodynamic grounds, on taking bromide ion as an example. A recent investigation<sup>30</sup> reports  $1.5$  and  $-2.20$  V for  $E_{\text{Br}^{\bullet}/\text{Br}^-}^{\circ}$  and  $E_{\text{PhBr}^{\bullet}/\text{PhBr}^{\bullet-}}^{\circ}$ , respectively, in DMF. The  $\Delta G^{\circ}$  of the  $\text{Ph}-\text{Br}$  bond is evaluated as  $72.6$  kcal mol<sup>-1</sup>. From these numbers, step (10) turns out to be endoergonic by ca.  $13$  kcal mol<sup>-1</sup> in this case!

'Good nucleophile'  $\text{Y}^- = ^-\text{CH}_2\text{COCH}_3$

$$\Delta G_{\text{PhY}^{\bullet-}}^{\circ} = -87 - 1 + 69 = -19 \text{ kcal mol}^{-1}$$

'Weak nucleophile'  $\text{Y}^- = \text{PhS}^-$

$$\Delta G_{\text{PhY}^{\bullet-}}^{\circ} = -68 + 2.3 + 62 = -3.7 \text{ kcal mol}^{-1}$$

'Unreactive nucleophile'  $\text{Y}^- = \text{PhO}^-$

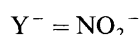
$$\Delta G_{\text{PhY}^{\bullet-}}^{\circ} = -67 + 5.1 + 67 = 5.1 \text{ kcal mol}^{-1}$$

'No-return nucleophile'  $\text{Y}^- = \text{Br}^-$

$$\Delta G_{\text{PhY}^{\bullet-}}^{\circ} = -73 + 35 + 51 = 13 \text{ kcal mol}^{-1}$$

'Strange nucleophiles'  $\text{Y}^- = \text{CN}^-$

$$\Delta G_{\text{PhY}^{\bullet-}}^{\circ} = -122 + 41.5 + 46 = -34 \text{ kcal mol}^{-1}$$



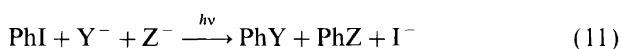
$$\Delta G_{\text{PhY}^{\bullet-}}^{\circ} = -58 + 16 + 19 = -23 \text{ kcal mol}^{-1}$$

*Scheme 1.* Thermodynamic driving force for the addition step:  $\text{Ph}^{\bullet} + \text{Y}^- \rightarrow \text{PhY}^{\bullet-}$  ( $\Delta G_{\text{PhY}^{\bullet-}}^{\circ} = -\Delta G_{\text{Ph-Y}}^{\circ} + FE_{\text{Y}^{\bullet}/\text{Y}^{\bullet-}}^{\circ} - FE_{\text{PhY}^{\bullet}/\text{PhY}^{\bullet-}}^{\circ}$ ). Analysis of the three contributing terms for some significant cases.

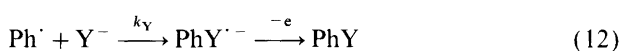
*Thermodynamic vs. kinetic data.* It was of interest to compare the thermodynamic driving force for the nucleophile/radical addition step with experimental rates of addition of the same nucleophile to phenyl radical. Unfortunately, only a few absolute reactivity determinations have been carried out for step (4). By a cyclic voltammetry approach, the research group of Savéant was able to measure the rate constant of addition of  $\text{PhS}^-$ ,  $\text{CH}_3\text{COCH}_2^-$  and  $(\text{EtO})_2\text{PO}^-$  ions to  $\text{Ph}^{\bullet}$  as  $2.6 \times 10^7$ ,  $2.7 \times 10^8$  and  $3.8 \times 10^8$  M<sup>-1</sup> s<sup>-1</sup>, respectively, in  $\text{NH}_3$  at  $-33$  °C.<sup>13c</sup> By making use of a radical clock, Beckwith obtained  $8 \times 10^7$  M<sup>-1</sup> s<sup>-1</sup> as the rate of addition of  $\text{PhS}^-$  to an *ortho*-alkoxy-substituted phenyl radical in  $\text{Me}_2\text{SO}$  at  $25$  °C.<sup>31</sup> It is notable that these rate constants are all below the diffusion limit, while the reactions of the same  $\text{PhS}^-$ ,  $\text{CH}_3\text{COCH}_2^-$  and  $(\text{EtO})_2\text{PO}^-$  nucleophiles with 1-naphthyl radical are all at the diffusion limit.<sup>32</sup> This finding has been explained by the fact that the  $\pi^*$  MO of the aromatic group, where the extra electron of  $\text{ArY}^{\bullet-}$  is going to reside, is higher in energy for phenyl than for naphthyl, therefore the

nucleophile/radical coupling with the phenyl group would be retarded.<sup>27,32</sup>

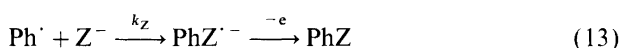
As a convenient alternative to absolute rate constant determinations, relative nucleophilic reactivities toward Ph<sup>·</sup> have been measured from competitive S<sub>RN</sub>1 reactions of pairs of nucleophiles. The rationale behind this approach is that, whenever two nucleophiles Y<sup>-</sup> and Z<sup>-</sup>, eqn. (11), are allowed to react together with PhI with suitable induction, the relative amounts of the two substitution products PhY and PhZ are bound to reflect the relative reactivity of the two nucleophiles ( $k_Y/k_Z$ , viz.,  $k_{rel}$ ) in their irreversible addition to Ph<sup>·</sup>, eqns. (12) and (13).<sup>16b,33</sup>



through



and



being

$$k_Y/k_Z = \frac{\ln([Y^-]_o/[Y^-]_t) - [\text{PhY}]_t}{\ln([Z^-]_o/[Z^-]_t) - [\text{PhZ}]_t} \quad (14)$$

The initiation step, where generation of PhI<sup>·-</sup> (and subsequently of Ph<sup>·</sup>) occurs, is, in this way, shared by the two nucleophiles, and the technique allows one to 'isolate' the competition of Y<sup>-</sup> and Z<sup>-</sup> for the same reactive intermediate (i.e., Ph<sup>·</sup>) from the overall reactivity. Table 4 shows these relative reactivities in Me<sub>2</sub>SO with respect to Me<sub>3</sub>CCOCH<sub>2</sub><sup>-</sup>, which was the reference compound in each competing pair of anions.

Other relative nucleophilic reactivities in liquid ammonia have already been obtained from competitive S<sub>RN</sub>1 reactions on PhX under photostimulation.<sup>33</sup> Relevant values obtained, i.e., 1.4 for (EtO)<sub>2</sub>PO<sup>-</sup>, and 0.08 for PhS<sup>-</sup>, both vs. Me<sub>3</sub>CCOCH<sub>2</sub><sup>-</sup>, are in very good agreement with those that can be determined (i.e., 1.4 and 0.09, with respect to CH<sub>3</sub>COCH<sub>2</sub><sup>-</sup>) from a knowledge of the absolute rate constants of addition of these nucleophiles to phenyl radical in the same solvent.<sup>13c</sup> Such agreement underlines the reliability of the method of competitive reactions for the present investigation. As a further substantiation of this approach, the lack of dependence of the relative nucleophilicity from the initiation method is indeed verified. For example, on changing the solvent from NH<sub>3</sub> to Me<sub>2</sub>SO, the relative reactivity of (EtO)<sub>2</sub>PO<sup>-</sup> vs. Me<sub>3</sub>CCOCH<sub>2</sub><sup>-</sup> under photostimulation of PhI increases from 1.4 to 2.2; the latter number is neatly reproduced as 2.4 under ferrous-ion induction.<sup>16b</sup> Analogously, the relative reactivity of EtCOCH(CH<sub>3</sub>)<sup>-</sup> vs. Me<sub>3</sub>CCOCH<sub>2</sub><sup>-</sup> is 1.4 under both ferrous-ion induction and spontaneous induction<sup>34</sup> in Me<sub>2</sub>SO solution.<sup>16b</sup> All these findings confirm that the reactivity ratios obtained do reflect the different efficiency

of the nucleophile/Ph<sup>·</sup> addition steps, regardless the way the radical was generated in the initiation.

Conversion of our  $k_{rel}$  data of Table 4 into absolute rate constants can be achieved from a knowledge of the above-reported rate constant (i.e.,  $8 \times 10^7 \text{ M}^{-1} \text{ s}^{-1}$ ) for reaction of PhS<sup>-</sup> with the *ortho*-alkoxy-substituted phenyl radical in Me<sub>2</sub>SO at 25 °C,<sup>31</sup> which is taken as a model of phenyl radical reactivity in step (4). The 'absolute' rate constants thus obtained (Table 4) once more confirm that the nucleophile/Ph<sup>·</sup> addition steps, even though fast, are slower than the diffusion limit.

By and large, the kinetic data confirm the thermodynamic predictions of eqn. (6). In fact, NH<sub>2</sub><sup>-</sup>, (EtO)<sub>2</sub>PO<sup>-</sup>, indenide and fluorenone anions are all more reactive than pinacolone enolate ion, taken as the reference ion, in agreement with the  $\Delta G_{\text{PhY}^{\cdot-}}$  determinations, approximate as they may be. Consistently, PhS<sup>-</sup> proves to be less reactive, while PhO<sup>-</sup> is unreactive. The same is true for acetylacetonate ion, even though lack of the  $\alpha$ -phenyl derivative prevents determination of the  $E_{\text{PhY/PhY}^{\cdot-}}^{\text{red}}$  in this case. It can also be seen that all anions more reactive than pinacolone enolate ion form a stronger bond with Ph<sup>·</sup>; consistently PhS<sup>-</sup> ion, which forms a weaker bond than the reference anion, is less reactive in the addition step. Therefore, the  $\Delta G_{\text{Ph-Y}}$  parameter appears to affect significantly not only the thermodynamic driving force, but also the activation process.

In Scheme 1, two nucleophiles displaying a 'strange' behaviour are reported. These are CN<sup>-</sup> and NO<sub>2</sub><sup>-</sup>. A quite low rate constant (ca.  $10^6 \text{ M}^{-1} \text{ s}^{-1}$  or lower) is reported for coupling of CN<sup>-</sup> with Ph<sup>·</sup>;<sup>27</sup> this 'low' value is strange, in view of the favourable thermodynamic driving force of  $-34 \text{ kcal mol}^{-1}$  determined for that step. Similarly, a favourable  $\Delta G_{\text{PhY}^{\cdot-}}$  value (i.e.,  $-23 \text{ kcal mol}^{-1}$ ) is determined for coupling of NO<sub>2</sub><sup>-</sup> with Ph<sup>·</sup>, even though no reactivity in a S<sub>RN</sub>1 process is observed.<sup>10b</sup> Lack of kinetic efficiency is confirmed here for CN<sup>-</sup>, since it fails to show any reactivity toward Ph<sup>·</sup> when competing with Me<sub>3</sub>CCOCH<sub>2</sub><sup>-</sup> in Me<sub>2</sub>SO (Table 4). In contrast, NO<sub>2</sub><sup>-</sup> becomes reactive in the corresponding competition experiment, while it fails to react with PhI in the absence of the other nucleophile. An analogous recovery of reactivity (i.e., 'entrainment')<sup>2b</sup> has already been put forward for the sluggish enolate ion from 2-indanone,<sup>16b</sup> when competing with Me<sub>3</sub>CCOCH<sub>2</sub><sup>-</sup> vs. PhI.

It can be observed that the addition processes of CN<sup>-</sup> and of NO<sub>2</sub><sup>-</sup> to Ph<sup>·</sup> are thermodynamically favoured, particularly in the case of the former ion, due to the relevant contribution of the  $\Delta G^\circ$  bond energy term (Scheme 1). Clearly, the kinetic efficiency of the Ph<sup>·</sup>/Y<sup>-</sup> coupling step is instead linked to the activation free energy, to which the three terms of eqn. (6) may offer contributions of different relative relevance. Savéant has demonstrated<sup>5,8</sup> that the relationship between the activation free energy and the standard free energy of an associative electron transfer reaction, such as that of eqn. (4), is formally identical with the quadratic

Marcus–Hush equation for outer-sphere electron transfer reactions.<sup>35</sup> A linearized version of the quadratic Marcus–Hush equation is given in eqn. (15).<sup>8</sup>

$$\Delta G_{\text{PhY}^\cdot}^\ddagger = -\text{BDE}_{\text{Ph-Y}}/4 + FE_{\text{Y}^\cdot/\text{Y}^-}/2 - FE_{\text{PhY}/\text{PhY}^\cdot}^\circ/4 - FE_{\text{Y}^\cdot/(\text{Y}^\cdot)}^\circ/4 + T\Delta S \quad (15)$$

Here, only a quarter of the homolytic bond dissociation energy of the bond being formed (concertedly with electron transfer) contributes to the  $\Delta G_{\text{PhY}^\cdot}^\ddagger$  value. Thus, the favourable contribution from formation of the strong Ph–CN bond could be outweighed by the high and positive oxidation potential of  $\text{CN}^-$  ion, whose unfavourable contribution is reduced by only one-half in eqn. (15). This was the explanation given for the ‘slow’ addition of  $\text{CN}^-$  to Ph·.<sup>8</sup> As for  $\text{NO}_2^-$  ion, its positive oxidation potential<sup>30</sup> prevents an efficient initiation step of the  $\text{S}_{\text{RN}}1$  reaction whenever  $\text{NO}_2^-$  is the only reacting nucleophile. When reacting in competition with the enolate ion, which instead is a good reductant, the initiation of the  $\text{S}_{\text{RN}}1$  process may occur efficiently, and phenyl radical is thereby produced. Coupling of  $\text{NO}_2^-$  with Ph· can then take place in keeping with the exoergonicity of that step, which is favoured by the  $FE_{\text{PhY}/\text{PhY}^\cdot}^{\text{red}}$  term in this particular case.

Unfortunately, the nucleophiles investigated in this study are very much heterogeneous in structure: this implies that their reorganization energy is not likely to be the same.<sup>5</sup> This prevents the construction of any significant  $\Delta G_{\text{PhY}^\cdot}^\ddagger$  vs.  $\Delta G_{\text{PhY}^\cdot}^\circ$  plot following Savéant’s guidelines.<sup>5,8</sup> If a more homogeneous set of  $\text{Y}^-$  species, and of the corresponding PhY substitution products, lend themselves to a thorough electrochemical investigation in the future, this drawback could be overcome.

## Conclusions

Inspection of the various features that govern nucleophilic reactivity in  $\text{S}_{\text{RN}}1$  processes has been attempted for a number of nucleophiles, with particular emphasis on the step comprising addition of the anions to phenyl radical in the propagation chain of the process. Determination of relevant electrochemical parameters, such as the oxidation potential of the nucleophiles and the reduction potential of the substitution products, has been attempted. Values of BDE for the C–Y bond formed in the Ph·/Y<sup>−</sup> addition step have been calculated for most of the substitution products reported in this study. The entropic contribution to the addition step has also been evaluated. From all these data, the thermodynamic driving force of the nucleophile/radical addition step has been obtained. Comparison of the thermodynamic driving force with experimental reactivity of the nucleophiles in the addition step to Ph· has become possible, and a number of significant cases have been presented.

## Experimental

**Instrumentation.** Most details have been given in previous publications.<sup>10,16,36</sup> A Rayonet reactor, fitted with 16 lamps emitting in the 350 nm region (Pyrex-filtered), was used in the photoinduced experiments. Cyclic voltammetry measurements were made using a standard three-electrode single-cell arrangement.<sup>37</sup> For oxidation potential determinations, an Amel 5000 potentiostat was used, and the cell was fitted either with a platinum working electrode (planar disk,  $\phi$  1 mm) or with a gold one ( $\phi$  0.5 mm), in combination with an aqueous SCE reference electrode. The latter was separated from the cell solution by means of a salt bridge containing the supporting electrolyte. The reduction potentials were determined with a home-made potentiostat<sup>37</sup> and a PARK model 175 generator, using a gold working electrode ( $\phi$  0.5 mm) and the SCE reference electrode. Platinum counter electrodes were always employed.

**Materials.** Iodobenzene and  $(\text{EtO})_2\text{PHO}$  were distilled from  $\text{CaH}_2$ . The precursors of most of the nucleophiles were distilled from anhydrous  $\text{K}_2\text{CO}_3$ ; other precursors were reagent grade commercial samples. Freshly sublimed *t*-BuOK was used to generate the anions. Commercial  $\text{Me}_2\text{SO}$  (C. Erba RPE, 99.5%) was stored over molecular sieves and flushed with argon for 30 min prior to use. THF was distilled from sodium–benzophenone ketyl, and stored under argon. Acetonitrile was distilled dry from  $\text{P}_2\text{O}_5$ . Tetrabutylammonium tetrafluoroborate (TBAF) was prepared<sup>38</sup> from  $\text{Bu}_4\text{N}^+ \text{HSO}_4^-$  (Aldrich) and  $\text{Na}^+ \text{BF}_4^-$  (Fluka) in water, recrystallized from ethyl acetate–light petroleum (b.p. 40–70 °C) and dried under vacuum ( $10^{-2}$  Torr) at 60 °C for 6 h.

**Reaction products.** Some products were already available from previous investigations.<sup>10,16</sup>  $\alpha$ -Phenylacetophenone (Fluka), 9-phenylfluorene (Aldrich), and 3-phenylindene (Schuchardt) were used as received.

**Competition experiments of different nucleophiles.** In a flame-dried glass-ware, a solution of 0.83 mmol of each precursor of the two nucleophiles (pinacolone being always the reference compound) and 0.22 g *t*-BuOK (2 mmol) in 13 ml  $\text{Me}_2\text{SO}$  was prepared under argon and stirred at room temperature for 5 min. After the addition of PhI (0.26 mmol), the flask was inserted in the photochemical reactor and the lamps switched on. Samples of the reaction mixture (ca. 4 ml) were taken at appropriate times,<sup>16</sup> quenched with acidic solution (10%  $\text{H}_2\text{SO}_4$ ), treated with the internal standard (biphenyl), and extracted with diethyl ether. GLC determination of the yield of the reaction products followed (4% typical error), a suitable response factor having been determined for the pure compounds. The relative nucleophilic reactivity was determined from GLC product yields by making use of the standard equation for competitive reactions.<sup>33</sup> The reported relative reactivities are the average of the

results of three injections for each of the sampling times (two or three).

**Determination of the oxidation potential of the nucleophiles by CV.** The anions were generated *in situ* in 0.1 or 0.4 M TBAF in Me<sub>2</sub>SO (C. Erba RPE) at 25 °C by the addition of *t*-BuOK (4 mM) to the parent precursor (2 mM) under argon. Use of other brands of Me<sub>2</sub>SO proved not to be equally effective. The choice of the supporting electrolyte proved to be not a trivial one: tetrabutylammonium tetrafluoroborate, prepared by exchange between NaBF<sub>4</sub> and Bu<sub>4</sub>NHSO<sub>4</sub> and then carefully crystallized,<sup>38</sup> gave even better results than commercial TBAF (FLUKA, puriss.). In some cases, LiClO<sub>4</sub> gave more reproducible results. A 500 mV s<sup>-1</sup> sweep scan was chosen after several attempts. The reproducibility of the measurements was not good enough to permit the observation of any significant variation of the *E*<sup>P</sup> value with sweep scan changes.<sup>14,39</sup> Better and more reproducible results were instead obtained in MeCN solution, under comparable conditions. The PhS<sup>-</sup> and PhO<sup>-</sup> ions were prepared in the electrochemical cell by neutralization of PhSH and PhOH, respectively, with a small aliquot of a 0.8 M Bu<sub>4</sub>N<sup>+</sup> OH<sup>-</sup> solution in MeOH (Fluka).

**Thiophenoxide ion.** This anion gives an irreversible CV wave for scan rates between 0.02 and 20 V s<sup>-1</sup>, with a continuous variation of the peak potential vs. the logarithm of the scan rate (*v*), as shown in Fig. 2. Two lines, having slope ( $\partial E^P/\partial \log v$ )<sub>25°C</sub> = 19.7 mV for lower scan rates and ( $\partial E^P/\partial \log v$ )<sub>25°C</sub> = 59.1 mV for higher scan rates, fit these experimental points: this is an indication of competition between the initial electron-transfer step, eqn. (16), and the follow-up dimerization step, eqn. (17).<sup>14</sup>

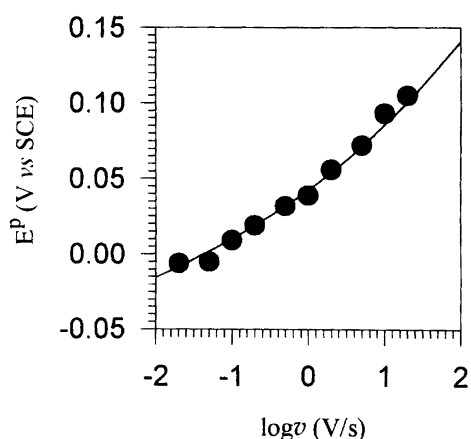


Fig. 2. Cyclic voltammetry of PhS<sup>-</sup> ion (1.95 mM) in 0.1 M Bu<sub>4</sub>NBF<sub>4</sub> in MeCN at a 0.5 mm gold disk electrode. Anodic peak potential (●) vs. the logarithm of scan rate *v*. The line represents the theoretically predicted variations for ( $k_G^2/Dk_d^{1/3}$ ) = 1.0 M<sup>1/3</sup> s<sup>-2/3</sup>.

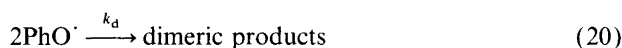
Assuming that the transfer coefficient is 0.5, this competition is controlled by the parameter *p*, eqn. (18),<sup>40</sup> where *k<sub>G</sub>* is the rate constant for the electron transfer, *k<sub>d</sub>* is the dimerization rate constant, *D* is the diffusion coefficient of the substrate and *C<sub>o</sub>* is the substrate concentration in the bulk solution. Fitting the theoretical (*E*<sup>o</sup> vs. log *v*) curve to the experimental points gives 1.0 M<sup>1/3</sup> s<sup>-2/3</sup> for the ratio ( $k_G^2/Dk_d^{1/3}$ ) and 0.096 V (taking *k<sub>d</sub>* = 6.3 × 10<sup>9</sup> M<sup>-1</sup> s<sup>-1</sup>)<sup>14</sup> for *E*<sup>o</sup> (compare with values of 1.1 M<sup>1/3</sup> s<sup>-2/3</sup> and 0.100 V, respectively, obtained by Savéant).<sup>14</sup>

$$p = 6^{1/3}(F/RT)^{-2/3}(k_G^2/k_d^{1/3}D)C_o^{1/3}v^{-2/3} \quad (18)$$

**Phenoxide ion.** This presents irreversible CV waves for scan rates between 0.1 and 10 V s<sup>-1</sup>, with a continuous variation of the peak potentials vs. the logarithm of scan rate as shown in Fig. 3. As for PhS<sup>-</sup>, even with PhO<sup>-</sup> there is competition between the initial electron transfer, eqn. (19),



and the follow-up dimerization step, eqn. (20).



which is governed by the parameter *p*. Fitting the theoretical (*E*<sup>P</sup> vs. log *v*) curve to the experimental points, provides 2.6 M<sup>1/3</sup> s<sup>-2/3</sup> for the ( $k_G^2/Dk_d^{1/3}$ ) ratio and 0.22 V for *E*<sup>o</sup> (assuming *k<sub>d</sub>* = 10<sup>9</sup> M<sup>-1</sup> s<sup>-1</sup>),<sup>17</sup> in line with an estimated *E*<sup>o</sup> value of 0.24 V.<sup>17</sup>

**Fluorenyl ion.** This presents irreversible cyclic voltammetric waves for scan rates between 0.1 and 20 V s<sup>-1</sup>. The experimental *E*<sup>P</sup> values, when plotted vs. log *v*, are fitted by a line with slope ( $\partial E^P/\partial \log v$ )<sub>25°C</sub> of 60 mV; it was not possible, therefore, to determine the *E*<sup>o</sup> for this anion.<sup>14</sup> A recent determination of *E*<sup>o</sup> of a series of

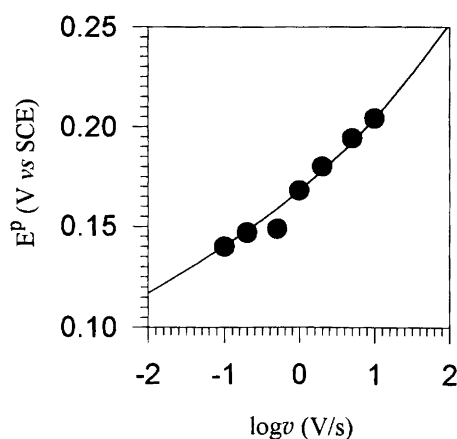


Fig. 3. Cyclic voltammetry of PhO<sup>-</sup> ion (2.1 mM) in 0.1 M Bu<sub>4</sub>NBF<sub>4</sub> in MeCN at a 0.5 mm gold disk electrode. Anodic peak potential (●) vs. the logarithm of scan rate *v*. The line represents the theoretically predicted variations for ( $k_G^2/Dk_d^{1/3}$ ) = 2.6 M<sup>1/3</sup> s<sup>-2/3</sup>.



substituted fluorenyl anions has been carried out with scan rates in the order of 30 000 V s<sup>-1</sup>.<sup>41</sup>  $E^\circ$  of  $-0.270$  V vs. NHE is reported for **6**; it can be converted to  $-0.51$  V vs. SCE, in good agreement with our  $E^p$  value of  $-0.55$  V (Table 1).

*Acetophenone enolate ion.* Consistent with the above, only irreversible CV waves were obtained for scan rates between 0.1 and 20 V s<sup>-1</sup>. The  $E^p$  vs.  $\log \nu$  plot did not allow the determination of the  $E^\circ$  value.

*Determination of the reduction potential of the substitution products by CV.* The concentration of the PhY species was 2 mM in 0.37 M TBAF solution in THF. The determinations were carried out at 25 °C under argon, at a 500 mV s<sup>-1</sup> sweep scan.

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## Appendix

*Enthalpies.* An example of calculation of the BDE is given in the case of Ph-CH<sub>2</sub>COPh. The  $\Delta_f H_{298}$  of PhCH<sub>2</sub>COPh is experimentally available<sup>24b</sup> as 5.3 kcal mol<sup>-1</sup>. Alternatively, it can be calculated from Benson's group increments,<sup>22</sup> as follows:

|                             |                                 |
|-----------------------------|---------------------------------|
| 10 C <sub>B</sub> -(H)      | 10 × 3.3 kcal mol <sup>-1</sup> |
| 1 C <sub>B</sub> -(C)       | 5.51 kcal mol <sup>-1</sup>     |
| 1 C <sub>B</sub> -(CO)      | 9.7 kcal mol <sup>-1</sup>      |
| 1 C-(CO)(C)(H) <sub>2</sub> | -5 kcal mol <sup>-1</sup>       |
| 1 CO-(C <sub>B</sub> )(C)   | -37.6 kcal mol <sup>-1</sup>    |

$$\Delta_f H_{298}(\text{PhCH}_2\text{COPh}) = 5.6 \text{ kcal mol}^{-1}$$

Good agreement between experimental and calculated values is evident. As for  $\Delta_f H_{298}$  of PhCOCH<sub>2</sub><sup>•</sup>, it is not experimentally available but can be obtained from the known BDE of the C-H bond of acetophenone (93 kcal mol<sup>-1</sup>),<sup>42</sup> and  $\Delta_f H_{298}$  of PhCOCH<sub>3</sub> ( $-20.7$  kcal mol<sup>-1</sup>),<sup>24b</sup> through the use of eqn. (9), the  $\Delta_f H_{298}$  (H<sup>•</sup>) term being 52.1 kcal mol<sup>-1</sup>.<sup>24c</sup>

$$\begin{aligned} \text{BDE}_{\text{C-H}} &= \Delta_f H_{298}(\text{PhCOCH}_2^\bullet) \\ &+ \Delta_f H_{298}(\text{H}^\bullet) - \Delta_f H_{298}(\text{PhCOCH}_3) \end{aligned}$$

From this,  $\Delta_f H_{298}(\text{PhCOCH}_2^\bullet)$  is determined to be 20.2 kcal mol<sup>-1</sup>. Eqn. (9) finally provides the BDE<sub>Ph-Y</sub> of the Ph-CH<sub>2</sub>COPh bond (reported in Table 3), as follows:

$$\begin{aligned} \text{BDE}_{\text{Ph-Y}} &= \Delta_f H_{298}(\text{PhCOCH}_2^\bullet) \\ &+ \Delta_f H_{298}(\text{Ph}^\bullet) - \Delta_f H_{298}(\text{PhCOCH}_2\text{Ph}) \end{aligned}$$

The value obtained is 96.0 kcal mol<sup>-1</sup>, and derives from use of 81.1 kcal mol<sup>-1</sup> as the most recent and reliable  $\Delta_f H_{298}(\text{Ph}^\bullet)$  value.<sup>25</sup> The  $\Delta_f H_{298}$  of the indenyl radical was obtained in the same way from the  $\Delta_f H_{298}(\text{indene})$ , which is 39.0 kcal mol<sup>-1</sup>,<sup>24b</sup> and the BDE of the allylic C-H bond of indene (84 kcal mol<sup>-1</sup>).<sup>24a</sup> Not being available,  $\Delta_f H_{298}$  of 1-phenylindene had to be calculated (as 64 kcal mol<sup>-1</sup>) from Benson's approach,<sup>22</sup> in order to determine the BDE<sub>Ph-Y</sub> of 1-phenylindene as 88 kcal mol<sup>-1</sup>.

The case of 9-phenylfluorene was more difficult, because no direct data were available. Since the C-9 atom of fluorene has sp<sup>3</sup> hybridization, it is comparable in structure to a benzhydryl carbon. Hence, we approximated the structure of 9-phenylfluorene with that of triphenylmethane.  $\Delta_f H_{298}(\text{Ph}_2\text{CH}^\bullet)$ <sup>24c</sup> is 69.1 kcal mol<sup>-1</sup> and  $\Delta_f H_{298}(\text{Ph}_3\text{CH})$  is 64.8.<sup>24b</sup> From these data, and the above  $\Delta_f H_{298}(\text{Ph}^\bullet)$  value, the BDE of the Ph<sub>2</sub>CH-Ph bond was calculated (85 kcal mol<sup>-1</sup>); it was assumed to provide a good estimate of the corresponding bond of 9-phenylfluorene.

Calculation of  $\Delta_f H_{298}$  for (EtO)<sub>2</sub>PO<sup>•</sup> and PhP(O)(OEt)<sub>2</sub> was even more difficult. We approached them from empirical additivity contributions, starting from experimental values of related structures,<sup>24b,c</sup> such as: PH<sub>2</sub><sup>•</sup>, PH<sub>3</sub>, PMe<sub>3</sub>, P(O)Me<sub>3</sub>, PEt<sub>3</sub>, PPh<sub>3</sub>, P(OEt)<sub>3</sub>, P(O)(OEt)<sub>3</sub>, MeP(O)(OEt)<sub>2</sub>. The data we give in Table 4 in this particular case must be taken bearing in mind the large approximations involved, even though the approach followed is the one exploited by Benson in the determination of his averaged group contributions.<sup>22</sup>

*Entropies.* In Table 2 unavailable  $S^\circ_{(\text{Y}^\bullet)}$  values were approximated with known  $S^\circ$  values of the corresponding HY species; in fact, in cases where both  $S^\circ_{(\text{Y}^\bullet)}$  and  $S^\circ_{(\text{HY})}$  values were available, the similarity of the two values<sup>20b,21</sup> suggested that the latter could reasonably well approximate the former. Extensive use of Benson's group increments<sup>22</sup> was made, in general. The result from use of the increments was corrected for the overall rotational symmetry number ( $s$ ) of the Ph-Y structure,<sup>21,22</sup> according to the relationship: symmetry correction =  $-R \ln s$ . The following  $s$  values were evaluated (given in parentheses) for these compounds: PhCH<sub>2</sub>COPh (2), PhCH<sub>2</sub>COCH<sub>3</sub> (6), Ph<sub>2</sub>O and Ph<sub>2</sub>S (8), Ph<sub>2</sub>CHCOCH<sub>3</sub> (12), *t*-BuOPh (18), PhCH<sub>2</sub>COCMe<sub>3</sub> (18), PhCH(COCH<sub>3</sub>)<sub>2</sub> (144). As an example, the  $S^\circ$  value for PhCH<sub>2</sub>COCH<sub>3</sub> is obtained as follows:

|                             |  |
|-----------------------------|--|
| 5 C <sub>B</sub> -(H)       | 5 × 11.5 cal mol <sup>-1</sup> K <sup>-1</sup> |
| 1 C <sub>B</sub> -(C)       | -7.7 cal mol <sup>-1</sup> K <sup>-1</sup>     |
| 1 C-(CO)(C)(H) <sub>2</sub> | 9.6 cal mol <sup>-1</sup> K <sup>-1</sup>      |
| 1 CO-(C) <sub>2</sub>       | 15 cal mol <sup>-1</sup> K <sup>-1</sup>       |
| 1 C-(CO)(H) <sub>3</sub>    | 30.4 cal mol <sup>-1</sup> K <sup>-1</sup>     |
| -R ln 6                     | -3.56 cal mol <sup>-1</sup> K <sup>-1</sup>    |

$$S^\circ(\text{PhCH}_2\text{COCH}_3) = 101.2 \text{ cal mol}^{-1} \text{ K}^{-1}$$

In the case of Ph-P(O)(OEt)<sub>2</sub>, due to the unavailabil-

ity of specific group increments, a  $T\Delta S_{\text{react}}^{\circ}$  value, which is an average of the other  $T\Delta S_{\text{react}}^{\circ}$  values reported in Table 2, was tentatively employed (i.e.,  $-13 \text{ kcal mol}^{-1}$ ). For compounds Ph-Y, derived from anions **6**, **8** and **10**, the  $T\Delta S_{\text{react}}^{\circ}$  correction of the analogous anions **5**, **7** and **11**, respectively, was tentatively taken.

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