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## Reducing properties of 1,2-dipyridyl-1,2-disodioethanes: chemical validation of theoretical and electrochemical predictions†

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The reducing properties of highly delocalized radical anions and dianions of 1,2-di(hetero)arylethenes were investigated by theoretical calculations at the PBE0/6-311+G(d,p)/IEFPCM level. The results correlated nicely with the reduction potentials determined by analysis of the voltammetric curves for the reduction of the parent alkenes, and this allowed a reliable scale for their relative reducing strength to be established. In full agreement with calculations and electrochemical results, use of the appropriate 1,2-dipyridyl-1,2-disodioethane as a base led to the successful  $\alpha$ -alkylation of bromophenylacetic acids under mild reaction conditions, thus avoiding the competitive reductive cleavage of aromatic C–Br bonds.

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### Introduction

The tunability of redox reactions is a topic of primary importance in chemistry, finding application in a variety of areas such as extension of the synthetic usefulness of reagents such as SmX<sub>2</sub>,<sup>1,2</sup> Ni(II)-salen<sup>3,4</sup> or neutral organic electron donors,<sup>5</sup> control of the particle size during the formation of metal nanoparticles,<sup>6</sup> or electrochemical performance of fuel cells.<sup>7</sup> 1,2-Diaryl-1,2-disodioethanes<sup>8</sup> constitute an easily accessible class of organometallic compounds endowed with interesting reducing properties. Besides applications as dinucleophiles in the diastereoselective synthesis of *trans*-1,2-diarylcyclopentanes<sup>9</sup> and borinanes,<sup>10</sup> we previously described their use as electron-transfer reagents for highly effective reductive eliminations in 1,2-hetero-disubstituted compounds<sup>11,12</sup> and degradations of aromatic persistent organic pollutants.<sup>13–17</sup>

A comparison between the electroreduction potentials of the 1,2-diarylethenes and the results obtained for the reduction of model compounds with the corresponding 1,2-diaryl-1,2-disodioethanes bearing different substituents allowed us to observe that the less delocalized dianions are the most powerful reducing agents, and *vice versa*.<sup>18</sup> These results were

substantiated by establishing that the outcome of the reactions between halogenated arylacetic acids and 1,2-diaryl-1,2-disodioethanes strongly depends on the nature of both partners. The reaction pattern was rationalized in terms of a competition between the ease of the reductive cleavage of the carbon halide bond and the reducing and basic properties of the vic-diorganometals. These observations were instrumental to set up mild reaction conditions for the chemoselective generation of the enediolates of 2-fluoro- and 2-chloro-phenylacetic acids, as well as trapping of these reactive species with different electrophiles.<sup>19</sup> However, our earlier attempts to extend such a procedure to the generation of enediolates of bromophenylacetic acids invariably led to the formation of phenylacetic acid as a main product. Reductive dehalogenation occurred even in the presence of 1,2-disodio-1-(2-pyridyl)phenylethane, *i.e.*, the mildest reducing reagent employed (Scheme 1).<sup>18,19</sup> On these grounds and looking for more selective reagents, we speculated that addition of further pyridyl rings could generate dianions endowed with an appropriate balance between reducing and basic properties thereby allowing, *inter alia*, their use in effective  $\alpha$ -functionalizations of bromophenylacetic acids.

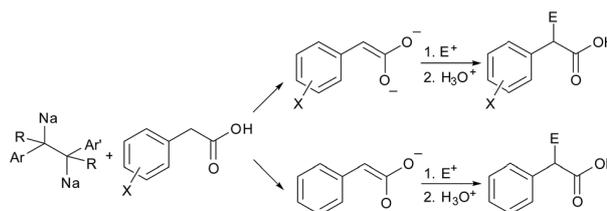
To check this hypothesis, we carried out a study aimed to verify whether the reducing properties of a series of dianions of

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† Electronic supplementary information (ESI) available: Sum of the electronic and zero point energy for minimum energy structures of compounds 1a–d, 2a–d, 3a–d. Structure of global minima for compounds 1a–d. Spin density for compounds 2a–d. <sup>1</sup>H NMR and <sup>13</sup>C NMR spectra of compounds 4a, 4a<sub>2</sub>, 6a and 6b. See DOI: 10.1039/c6ra03303b



Scheme 1 Competing basic and reducing properties of 1,2-diaryl-1,2-disodioethanes (from ref. 19). E<sup>+</sup> = electrophile.

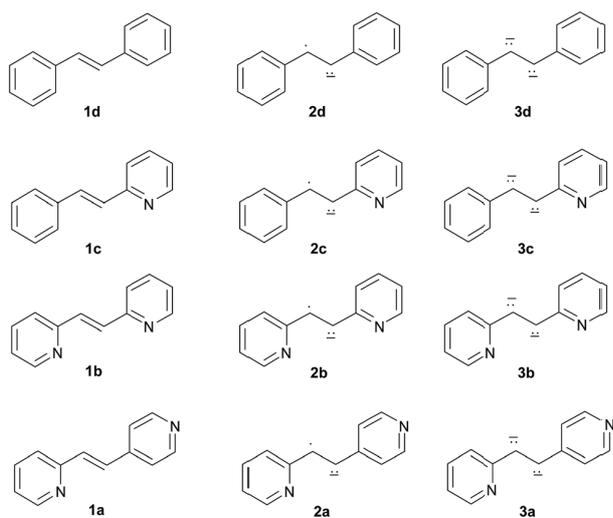


Chart 1 Formulas of the investigated 1,2-diarylethenes (1a–d) and corresponding radical anions (2a–d) and dianions (3a–d).

1,2-diarylethenes (3a–d, Chart 1) could be predicted by density functional theory (DFT) calculations, verified electrochemically, and then tested experimentally. The DFT computed electron affinities nicely correlate with the electrochemical reduction potentials of the parent alkenes (1a–d, Chart 1). The outcome of the DFT and electrochemical analyses was checked by preparing the sodium dianions of 1-(2-pyridyl)-2-(4-pyridyl)ethane (1a) and 1,2-di(2-pyridyl)ethane (1b) and then using them in reactions with halogenated benzoic and arylacetic acids.

## Experimental section

### Materials

Diarylalkenes 1a–d are commercially available and were purified by distillation or recrystallization immediately prior to use. Benzoic acids, 5a–d, and arylacetic acids, 5e–g, are commercially available. 18-crown-5 was distilled *in vacuo* immediately prior to use. Tetrahydrofuran (THF) was distilled from Na/K alloy under N<sub>2</sub> immediately prior to use. *N,N*-Dimethylformamide (DMF) was treated with anhydrous Na<sub>2</sub>CO<sub>3</sub> and distilled under a nitrogen atmosphere. Tetra-*n*-butylammonium perchlorate (TBAP) was recrystallized from a 2 : 1 ethanol–water solution and dried at 60 °C under vacuum.

### Instruments and methods

<sup>1</sup>H NMR spectra were recorded at 300 or 400 MHz and <sup>13</sup>C NMR spectra were recorded at 75 or 100 MHz in CDCl<sub>3</sub> with SiMe<sub>4</sub> as internal standard. Deuterium incorporation was calculated by monitoring the <sup>1</sup>H NMR spectra of crude reaction mixtures, and comparing the integration of the signal corresponding to protons in the arylmethyl (or heteroaryl) position with that of known signals. Resonances of the CHD protons are shifted 0.02–0.04 ppm ( $\delta$ ) upfield relative to the resonances of the corresponding CH<sub>2</sub> protons; the resonances of the arylmethyl CHD carbons appear as triplets ( $J = 18$ –20 Hz) shifted 0.3–0.5 ppm ( $\delta$ ) upfield relatively to the corresponding

arylmethyl (or heteroarylmethyl) CH<sub>2</sub> carbons. IR spectra were recorded on a FT-IR Jasco 680 P. Flash chromatography was performed on Merck silica gel 60 (40–63  $\mu$ m), and TLC analyses on Macherey-Nagel silica gel pre-coated plastic sheets (0.20 mm). Elemental analyses were performed by the microanalytical laboratory of the Dipartimento di Chimica e Farmacia, Università di Sassari.

### Computational details

Structure optimizations of compounds 1, of the corresponding radical anions, 2 and dianions, 3, were performed at the DFT level employing the PBE0 functional,<sup>20</sup> a parameter-free hybrid variant of the Perdew, Burke and Ernzerhof (PBE) generalized gradient functional,<sup>21</sup> as implemented in the commercially available suite of programs GAUSSIAN 09.<sup>22</sup> The 6-311+G(d,p) basis set was employed for all atoms. Unconstrained geometry vibrational analysis was carried out at the same level of theory to check the character of the stationary points and to calculate the thermochemistry data. In absence of coordinating cations a planar geometry was observed for all studied compounds. Calculations were performed *in vacuo* and with a polarizable continuum model of the solvent (DMF,  $\epsilon = 37$ ). We used the current implementation in Gaussian 09 (ref. 22) of PCM<sup>23</sup> performing a reaction field calculation with the integral equation formalism IEFPCM model.<sup>24</sup>

### Electrochemical investigations

The cyclic-voltammetry experiments were carried out in DMF containing 0.1 M TBAP, under an argon atmosphere in a glass cell thermostatted at 25 °C. The working electrode was a glassy carbon disk ( $9.64 \times 10^{-3}$  cm<sup>2</sup>), prepared and activated as already described.<sup>25</sup> A Pt plate was used as the counter electrode and Ag/AgCl as the reference electrode. Calibration of the latter was performed by addition of ferrocene at the end of the experiments; in this specific solvent/electrolyte system, the ferricenium/ferrocene redox couple has  $E^\circ = 0.464$  V against the KCl saturated calomel electrode (SCE). Potential values are reported against SCE. We used a CHI 660c electrochemical workstation, and the feedback correction was applied to minimize the ohmic drop between the working and the reference electrodes.

### General procedure for the generation of dianions 3a–d

0.1 M solutions of diorganometal 3bNa<sub>2</sub>–dNa<sub>2</sub> in dry THF were prepared as described previously.<sup>9,11,13–15</sup> 0.1 M solutions of diorganometal 3aNa<sub>2</sub> were generated according to a similar procedure by reacting 1-(2-pyridyl)-2-(4-pyridyl)ethene, 1a, under an Ar atmosphere with an excess of Na metal (4 equiv.) in dry THF at 0 °C during 12 h. After removing the excess of the metal, formation of the desired dianion can be evidenced by quenching separate aliquots of the resulting mixture with H<sub>2</sub>O (or D<sub>2</sub>O), followed by <sup>1</sup>H- and <sup>13</sup>C-NMR analyses of the reaction product, characterized as follows:

**1-(2-Pyridyl)-2-(4-pyridyl)ethane, 4a.** Purified by flash chromatography (CH<sub>2</sub>Cl<sub>2</sub>/Et<sub>3</sub>N = 10 : 1), light yellow oil.  $R_f = 0.48$  (CH<sub>2</sub>Cl<sub>2</sub>/Et<sub>3</sub>N = 10 : 1); Anal. found: C, 78.02; H, 6.81; N = 15.07;

$C_{12}H_{12}N_2$  requires: C, 78.23; H, 6.57; N, 15.21; IR (nujol) 1589  $cm^{-1}$ ;  $^1H$  NMR (400 MHz,  $CDCl_3$ ):  $\delta$  3.05–3.13 (4H, m), 7.06 (1H, d,  $J = 7.6$  Hz), 7.09–7.17 (3H, m), 7.57 (td, 1H,  $J = 7.8, 1.8$  Hz), 8.47 (2H, d,  $J = 4.4$  Hz), 8.57 (1H, d,  $J = 4.0$  Hz);  $^{13}C$  NMR (100 MHz,  $CDCl_3$ ):  $\delta$  34.9, 38.6, 121.4, 122.9, 123.8, 136.3, 149.4, 149.6, 150.3, 160.1.

#### General procedure for the reductive dehalogenation of halogenated benzoic acids 5a–c

24 mL of a metal free 0.1 M solution of a diorganometal  $3Na_2$  (2.4 mmol), was added to a solution of the appropriate benzoic acid 5a–c (1.2 mmol) dissolved in 5 mL of dry THF and chilled at 0 °C. The mixture was vigorously stirred and allowed to reach rt over 12 h, after which time it was quenched by slow dropwise addition of  $H_2O$  (15 mL). The organic solvent was evaporated *in vacuo* and the resulting mixture was extracted with  $CH_2Cl_2$  ( $3 \times 10$  mL). The aqueous phase was acidified with 1 N HCl, extracted with  $CH_2Cl_2$  ( $3 \times 10$  mL), and the organic phases were collected, washed with  $H_2O$  ( $1 \times 10$  mL), brine (10 mL), and dried ( $Na_2SO_4$ ). After filtration and evaporation of the solvent, the resulting mixture was analyzed by  $^1H$  NMR. The outcome of the reaction was assessed by comparing the spectrum with those of commercially available samples. In some reactions, the metal free diorganometal solution was allowed to equilibrate during 1 h at 0 °C in the presence of 0.95 mL of 15-crown-5 (4.8 mmol, 1.05 g) before reacting it with the appropriate benzoic acid under otherwise identical conditions.

#### General procedure for the metalation of arylacetic acids 5e,f

24 mL of a metal free 0.1 M solution of diorganometal  $3Na_2$  (2.4 mmol) was added at 0 °C to a solution of the appropriate arylacetic acid 5e,f (1.2 mmol) dissolved in 5 mL of dry THF. The resulting mixture was vigorously stirred for 2 h at the same temperature, after which time it was quenched by slow dropwise addition of  $H_2O$  (15 mL), followed by work up of the reaction mixture as described above. Quenching with  $D_2O$  was realized by adding 0.75 mL of  $D_2O$  to the reduction mixture chilled at 0 °C, followed after 10 minutes stirring by slow dropwise addition of  $H_2O$  (15 mL), and work up as described above. The outcome of the reaction was assessed by comparing the  $^1H$ - and  $^{13}C$ -NMR spectra of recovered product with those of commercially available samples.

#### General procedure for the alkylation of arylacetic acids 5e,f

24 mL of a metal free 0.1 M solution of diorganometal  $3aNa_2$  (2.4 mmol) was added to a solution of the appropriate bromoarylacetic acid 5e,f (1.2 mmol) dissolved in 5 mL of dry THF and chilled at –20 °C, and the resulting mixture was vigorously stirred for 2 h at the same temperature. To the resulting dark brown mixture, chilled at the same temperature, were added 1.5 mmol of the appropriate electrophile. The resulting mixture was vigorously stirred and allowed to reach rt overnight, after which time it was quenched by slow dropwise addition of  $H_2O$  (15 mL), followed by work up of the reaction mixture as described above. Crude reaction products were purified and characterized as reported below.

**2-(2-Bromophenyl)-3-methylbutanoic acid, 6a.** Purified by flash chromatography (petroleum ether/AcOEt = 7 : 3), white powder.  $R_f = 0.65$  (petroleum ether/AcOEt = 7 : 3); Anal. found: C, 51.32; H, 5.06;  $C_{11}H_{13}BrO_2$  requires: C, 51.38; H, 5.10; IR (nujol) 1708  $cm^{-1}$ ;  $^1H$  NMR (300 MHz,  $CDCl_3$ ):  $\delta$  0.74 (3H, d,  $J = 6.9$  Hz), 1.12 (3H, d,  $J = 6.3$  Hz), 2.25–2.40 (1H, m), 3.97 (1H, d,  $J = 10.5$  Hz), 7.11 (1H, ddd,  $J = 7.9, 7.4, 1.5$  Hz), 7.29 (1H, td,  $J = 8.1, 1.2$  Hz), 7.54 (2H, dd,  $J = 8.1, 1.2$  Hz);  $^{13}C$  NMR (75 MHz,  $CDCl_3$ ):  $\delta$  19.5, 21.2, 32.3, 56.9, 125.7, 127.7, 128.7, 129.0, 132.9, 137.2, 179.4.

**2-(2-Bromophenyl)hexanoic acid, 6b.** Purified by flash chromatography (petroleum ether/AcOEt = 7 : 3), pale yellow oil.  $R_f = 0.55$  (petroleum ether/AcOEt = 7 : 3); Anal. found: C, 53.19; H, 5.54;  $C_{12}H_{15}BrO_2$  requires: C, 53.15; H, 5.58; IR (neat) 1708  $cm^{-1}$ ;  $^1H$  NMR (300 MHz,  $CDCl_3$ ):  $\delta$  0.90 (3H, d,  $J = 6.9$  Hz), 1.24–1.42 (4H, m), 1.75–1.90 (1H, m), 2.05–2.18 (1H, m, CH), 4.24 (1H, d,  $J = 7.5$  Hz), 7.14 (1H, td,  $J = 7.8, 1.8$  Hz), 7.31 (1H, td,  $J = 7.2, 1.2$  Hz); 7.42 (1H, dd,  $J = 7.8, 1.8$  Hz); 7.59 (1H, dd,  $J = 7.8, 1.2$  Hz);  $^{13}C$  NMR (75 MHz,  $CDCl_3$ ):  $\delta$  13.8, 22.4, 29.4, 32.5, 49.8, 125.0, 127.7, 128.7, 128.7, 133.0, 138.1, 180.0.

**2-(4-Bromophenyl)propanoic acid, 6c.**<sup>26</sup> Purified by flash chromatography (petroleum ether/AcOEt = 7 : 3),  $R_f = 0.49$  (petroleum ether/AcOEt = 7 : 3); white powder, mp 79–81 °C (heptane); IR (nujol) 1704  $cm^{-1}$ ;  $^1H$  NMR (400 MHz,  $CDCl_3$ ):  $\delta$  0.90 (3H, d,  $J = 7.2$  Hz), 1.78 (1H, dpent,  $J = 14.4, 7.2$  Hz), 2.08 (1H, dpent,  $J = 14.4, 7.2$  Hz), 3.42 (1H, d,  $J = 7.2$  Hz), 7.15–7.21 (2H, m), 7.42–7.47 (2H, m);  $^{13}C$  NMR (100 MHz,  $CDCl_3$ ):  $\delta$  12.0, 26.2, 52.7, 121.4, 139.8, 131.7, 137.3, 179.5.

## Results and discussion

### Computational results

The structures and energies of the neutral, radical-anion, and dianion forms of compounds **a–d** *in vacuo* were modelled at the PBE0/6-311+G(d,p) level.<sup>20</sup> The solvent effect on the total molecular energy was estimated for DMF ( $\epsilon = 37$ ) by using the polarized continuum model<sup>24</sup> at the PBE0/6-311+G(d,p)/IEFPCM(DMF) level. As expected for structures in the absence of coordinating ions, all compounds are planar independently of the oxidation state, a geometry that allows attaining maximum electron delocalization.

A single minimum is observed for stilbene **1d** and its radical anion **2d** and dianion **3d**. On the other hand, for stilbazole **1c**, 1,2-di(2-pyridyl)ethane **1b**, and 1-(2-pyridyl)-2-(4-pyridyl)ethane **1a**, as well as for their radical anions and dianions, the minimum energy structures are two, three, and two, respectively. For all compounds the structural difference between the minima consists in the value of the dihedral angle  $C_e=C_e-C_i=N$ , where  $C_e$  is the C atoms of the ethene moiety (or of its reduced forms) and  $C_i$  is the *ipso* carbon atom of the aromatic ring. This dihedral angle may attain a value of either 0° or 180°, but the latter is favoured in most of the compounds. No exception to such preference is observed when the solvent is included in the calculations, whereas for calculations *in vacuo* we observed some exceptions for the dianions (Table S1, ESI†); global minima of compounds **1a–d** are represented in Fig. S1 (ESI†). Another important difference between the results *in*

Table 1 Electron affinity data for 1,2-diarylethenes 1

Entry	Substrate (eV)	EA <sub>1</sub> <sup>a</sup> ( <i>vacuo</i> ) (eV)	EA <sub>2</sub> <sup>b</sup> ( <i>vacuo</i> ) (eV)	EA <sub>1</sub> <sup>a</sup> (DMF) (eV)	EA <sub>2</sub> <sup>b</sup> (DMF) (eV)
1	<b>1a</b>	1.081	-1.822	2.796	4.961
2	<b>1b</b>	0.849	-2.238	2.700	4.775
3	<b>1c</b>	0.726	-2.475	2.498	4.322
4	<b>1d</b>	0.597	-2.698	2.269	3.847

<sup>a</sup> Single electron affinity. <sup>b</sup> Double electron affinity.

*vacuo* and in solution is the positive formation energy of the dianions in the former, which indicates that without inclusion of the solvent contribution the uptake of two negative charges makes the system less stable.

For compounds **1a–d**, the single (EA<sub>1</sub>) and double (EA<sub>2</sub>) electron affinities were calculated as the negative of the enthalpy change at 0 K and 1 atm,<sup>27</sup> from the neutral species to the corresponding radical anions or dianions, respectively. For each compound and charge state, the geometry was individually optimized. The calculated EA values decrease in the order **a** > **b** > **c** > **d** for both the radical anion and the dianion series no matter whether the calculations refer to *vacuo* or include the solvent effect (Table 1). These results, therefore, support our hypothesis that more delocalized dianions are milder reducing agents.

In the stilbene radical anion **2d**, the highest spin density sites are found at the ethene moiety, the *para* position of the

benzene rings and, to a smaller extent, the *ortho* positions. When CH groups in these ring positions are substituted by the more electronegative nitrogen atom (**2a**, **2b**, **2c**), the spin density changes by involving the nitrogen atom(s) quite significantly (Fig. S2, ESI<sup>†</sup>). The corresponding molecular electrostatic potential (MEP) profiles (Fig. 1) show that except for the stilbene radical anion **2d** and dianion **3d**, in which the region with the highest electrostatic potential corresponds to the ethene portion, for all other ions the highest potential is found in the ring, in the area close to nitrogen atoms, which withdraw the charge from the ethene portion.

#### Electrochemical analysis

The redox behaviour of **1a** and **1b** was studied by cyclic voltammetry (CV) to determine their formal reduction potential ( $E^\circ$ ) values, and then compare them to those determined previously for **1c** and **1d** (ref. 18) and the outcome of the calculations. The measurements were carried out in DMF/0.1 M TBAP with a glassy carbon microdisk electrode. For both compounds, the CV pattern shows two reduction peaks (Fig. 2). The first peak corresponds to the reversible formation of the radical anion, whereas the dianion forms at the second peak. At low potential-scan rates ( $\nu$ ), the latter is chemically irreversible. As previously observed for **1c** and **1d**,<sup>18</sup> irreversibility is attributed to protonation of the basic dianion by the residual water present in DMF, a quite common behaviour observed for the electroreduction of many unsaturated and aromatic compounds in formally aprotic solvents.<sup>28</sup> By increasing  $\nu$  and for both compounds, an anodic peak associated with the second cathodic peak starts becoming visible, which means that the lifetime of the dianions is now comparable with the CV time-scale. The electroreduction of **1a** and **1b** differs from that of **1c** and **1d** in two main aspects. First, the formation of the radical anions of **1a** and **1b** is thermodynamically easier than that of **1c** and **1d** (Table 2). Second, as opposed to **1c** and **1d**, the chemical reversibility of the second peak of **1a** and **1b** starts emerging upon increasing  $\nu$ , which points to a relatively slower protonation rate and thus lower basicity of the corresponding dianions. The comparison between the  $\nu$  dependence of the second peak of **1a** and **1b** shows that the former yields a less basic dianion than the latter.

For both reduction processes, the  $E^\circ$  could be calculated as the half-sum of the anodic and the cathodic peak potentials, using the CV data at high-scan rates for the second electron transfer. The  $E^\circ$  values are listed in Table 2 in comparison with the corresponding values for **1c** and **1d**. The dianions of **1c** and **1d** are

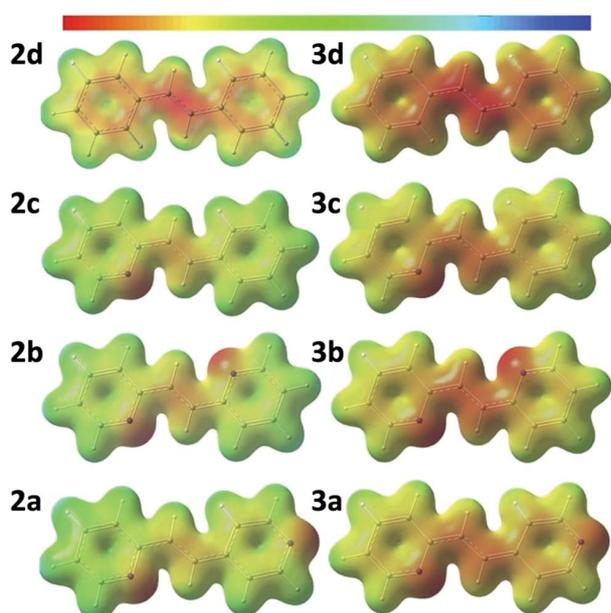


Fig. 1 Electrostatic potential mapped on an electron density isosurface (0.02 au  $\text{\AA}^{-2}$ ). Red coloured regions are those with the largest negative potential (varying from -0.19 to -0.46 au, depending on the compound and on the oxidation state); as the potential become less negative or even positive, the colour changes according to the scale reported on the top of the figure. The blue colour on the right-hand side of the scale corresponds to a positive potential having an absolute value equal to that of the largest negative potential (*i.e.* varying from 0.19 to 0.46 au depending on the compound).

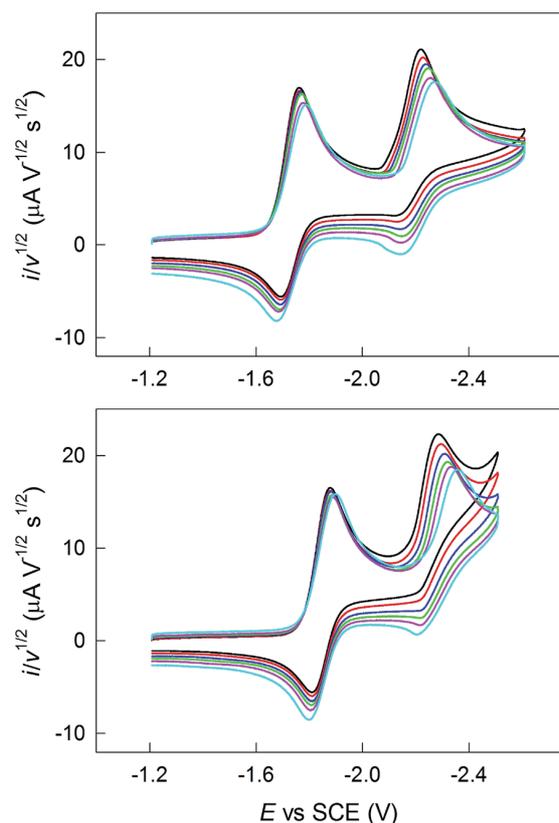


Fig. 2 CV curves for the reduction of 2.4 mM **1a** (upper graph) and 2.3 mM **1b** (lower graph) in DMF/0.1 M TBAP. The current is normalized for the scan rate. The curves were obtained at 0.1, 0.2, 0.5, 1, 2, and 5  $\text{V s}^{-1}$  (larger  $\nu$  values correspond to a more chemically-reversible, negatively-shifted second peak). Glassy-carbon electrode, 25 °C.

Table 2  $E^\circ$  data for 1,2-diarylethenes **1**<sup>a</sup>

Entry	Substrate	$E_1^\circ$ (V)	$E_2^\circ$ (V)
1	<b>1a</b>	-1.729	-2.188
2	<b>1b</b>	-1.846	-2.261
3	<b>1c</b>	-2.003 <sup>b</sup>	-2.485 <sup>b</sup>
4	<b>1d</b>	-2.182 <sup>b</sup>	-2.700 <sup>b</sup>

<sup>a</sup> DMF/0.1 M TBAP, glassy carbon electrode, 25 °C. <sup>b</sup> Determined as explained in the text.

very basic species and thus even in freshly distilled DMF no chemical reversibility can be attained at  $\nu$  as large as  $100 \text{ V s}^{-1}$ . For both compounds at low scan rates, the pertinent peak potential ( $E_p$ ) shifts negatively by 30 mV per decade change in  $\nu$ . This value is as expected for a first-order reaction<sup>29</sup> and is thus in agreement with protonation of the dianion by residual water present in sufficiently large amount (pseudo-first order conditions). By working in the presence of activated alumina, Parker and co-workers<sup>30</sup> could determine the  $E_2^\circ$  of **1d** to be  $-2.700 \text{ V}$ . From such value, use of the observed  $E_p$  values and the equation describing the effect of a first-order reaction on  $E_p$ <sup>16</sup> yields a pseudo first-order protonation rate constant of  $5 \times 10^4 \text{ s}^{-1}$ . The

reduction of **1c** was studied in the same solvent and thus in the presence of the same amount of water. A comparison between the voltammetric behaviour of the second peak of **1b** and **1c** indicates that introduction of nitrogen makes the dianion less basic, and thus one can safely infer that the pseudo first-order

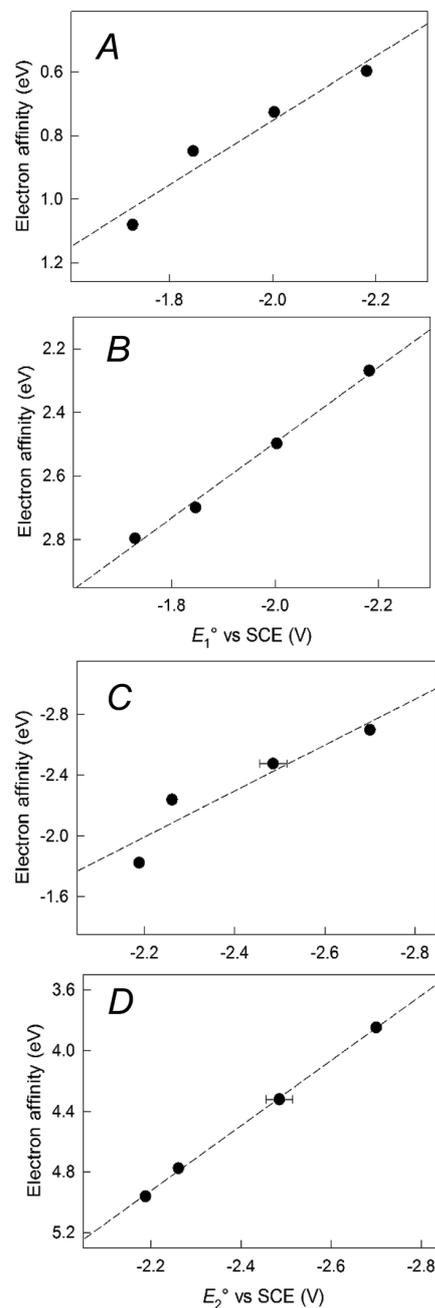
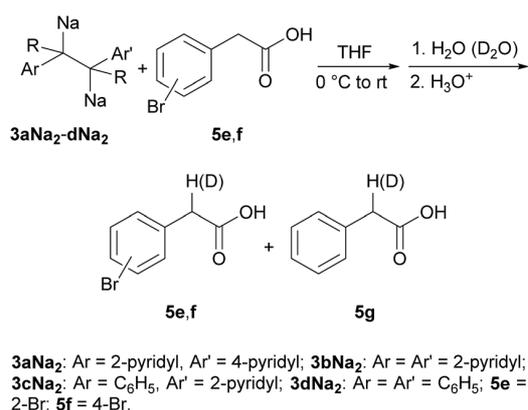


Fig. 3 Correlation between the computed single (A and B) and double (C and D) electron affinities of compounds **1a–d** and the formal potentials  $E_1^\circ$  and  $E_2^\circ$ . The graphs A and C refer to the calculations performed *in vacuo* at the PBE0/6-311+G(d,p) level, whereas the graphs B and D refer to the calculations performed by including the presence of DMF ( $\epsilon = 37$ ). The  $r^2$  values of the linear regressions are: 0.938 (A), 0.994 (B), 0.877 (C), 0.999 (D). For the error bar associated to the formation of **3c**, see text.





Scheme 4 Reaction of 1,2-diaryl-1,2-disodioethanes **3Na<sub>2</sub>** with bromophenylacetic acids.

Table 3 Reactions of 1,2-diaryl-1,2-disodioethanes **3Na<sub>2</sub>** with halogenated benzoic acids **5a-c**<sup>a</sup>

Entry	Diorganometal	Substrate (X=)	Recovered substrate <sup>b</sup> (%)	<b>5d</b> <sup>b</sup> (%)
1	<b>3aNa<sub>2</sub></b>	<b>5a</b> , X = F	<b>5a</b> , >99	<1 <sup>c</sup>
2	<b>3aNa<sub>2</sub></b>	<b>5b</b> , X = Cl	<b>5b</b> , 61	39
3	<b>3aNa<sub>2</sub></b>	<b>5c</b> , X = Br	<b>5c</b> , 17	83 <sup>c</sup>
4	<b>3bNa<sub>2</sub></b>	<b>5a</b> , X = F	<b>5a</b> , >99	<1
5	<b>3bNa<sub>2</sub></b>	<b>5b</b> , X = Cl	<b>5b</b> , 6	94
6	<b>3bNa<sub>2</sub></b>	<b>5c</b> , X = Br	<b>5c</b> , <1	>99
7	<b>3cNa<sub>2</sub></b>	<b>5a</b> , X = F	<b>5a</b> , 69 <sup>d</sup>	31 <sup>d</sup>
8	<b>3cNa<sub>2</sub></b>	<b>5b</b> , X = Cl	<b>5b</b> , <1 <sup>d</sup>	>99 <sup>d</sup>
9	<b>3cNa<sub>2</sub></b>	<b>5c</b> , X = Br	<b>5c</b> , <1	>99
10	<b>3dNa<sub>2</sub></b>	<b>5a</b> , X = F	<b>5a</b> , 20 <sup>d</sup>	80 <sup>d</sup>
11	<b>3dNa<sub>2</sub></b>	<b>5b</b> , X = Cl	<b>5b</b> , <1 <sup>c,d</sup>	>99 <sup>c,d</sup>
12	<b>3dNa<sub>2</sub></b>	<b>5c</b> , X = Br	<b>5c</b> , <1 <sup>c</sup>	>99 <sup>c</sup>

<sup>a</sup> All reactions were run in dry THF, during 12 h, with a dianion/carboxylic acid molar ratio = 2 : 1. <sup>b</sup> As determined by <sup>1</sup>H NMR spectroscopic analyses of crude reaction mixtures. <sup>c</sup> Addition of 2 equiv. of 15-crown-5 to the dianion, followed by 1 h equilibration at 0 °C before addition of the benzoic acid, afforded a comparable result. <sup>d</sup> Ref. 13.

**3aNa<sub>2</sub>** and **3bNa<sub>2</sub>**. Whereas reaction with 4-fluorobenzoic acid **5a** led to the recovery of the unreacted acid in quantitative yield (Table 3, entries 1 and 4), the reductions of 4-chlorobenzoic acid **5b** (Table 3, entry 2 vs. entry 5) and 4-bromobenzoic acid **5c** (Table 3, entry 3 vs. entry 6) allow discriminating that dianion **3aNa<sub>2</sub>** is a less powerful reductant than **3bNa<sub>2</sub>**.

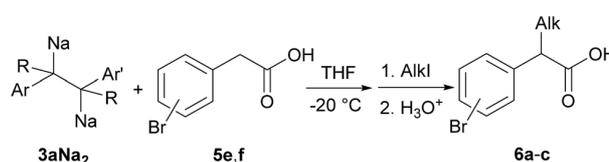
Finally, for the sake of better comparison with the reducing power assessed electrochemically, in which only loose ion pairs may form, some reductions (Table 3, entries 1, 3, 11 and 12) were performed after equilibrating solutions of dianions **3aNa<sub>2</sub>** and **3dNa<sub>2</sub>** with 15-crown-5 (see the Experimental section), which has a high binding affinity for sodium cation. Importantly, no significant modifications of the relative reducing power of the above mentioned dianions was observed.

To evaluate the competition between the reducing and basic properties of these diorganometals, we investigated their reactivity toward 2-bromo- and 4-bromophenylacetic acids, **5e** and **5f**,

Table 4 Reactions of 1,2-diaryl-1,2-disodioethane, **3Na<sub>2</sub>**, with bromophenylacetic acids **5e,f**<sup>a</sup>

Entry	Diorganometal	Substrate	Recovered substrate (%) <sup>b</sup>	<b>5g</b> (%) <sup>b</sup>
1	<b>3aNa<sub>2</sub></b>	<b>5e</b>	<b>5e</b> , 82 (75)	18
2	<b>3aNa<sub>2</sub></b>	<b>5f</b>	<b>5f</b> , 90 (91)	10 (66)
3	<b>3bNa<sub>2</sub></b>	<b>5f</b>	<b>5f</b> , 68 (76)	32 (65)
4	<b>3cNa<sub>2</sub></b>	<b>5e</b>	<b>5e</b> , 10 (90) <sup>c</sup>	90 (89) <sup>c</sup>
5	<b>3dNa<sub>2</sub></b>	<b>5e</b>	<b>5e</b> , <5 <sup>c</sup>	>95 (78) <sup>f</sup>

<sup>a</sup> All reactions were run in dry THF, during 12 h, with a diorganometal/carboxylic acid molar ratio = 2 : 1. <sup>b</sup> As determined by <sup>1</sup>H NMR spectroscopic analyses of crude reaction mixtures; the numbers in parenthesis refer to the percentage of hydrogen substitution for deuterium. <sup>c</sup> Ref. 19.



**5e**: 2-Br; **5f**: 4-Br; **6a**, 2-Br, Alk = (CH<sub>3</sub>)<sub>2</sub>CH, 52%; **6b**, 2-Br, Alk = *n*-C<sub>4</sub>H<sub>9</sub>, 69%; **6c**, 4-Br, Alk = CH<sub>3</sub>CH<sub>2</sub>, 85%; reported yields refers to isolated products

Scheme 5 Reactions of 1-(2-pyridyl)-2-(4-pyridyl)-1,2-disodioethane **3aNa<sub>2</sub>** with bromoarylacetic acids and reactions with alkyl iodides.

under closely related reaction conditions (Scheme 4). The outcome of these reactions, alternatively quenched with H<sub>2</sub>O or D<sub>2</sub>O, is summarized in Table 4, together with selected results of comparable reactions run with dianions **3cNa<sub>2</sub>** and **3dNa<sub>2</sub>**.<sup>19</sup> Once again, these results confirm the same scale of reducing power of the diorganometals, *i.e.*, **3aNa<sub>2</sub>** < **3bNa<sub>2</sub>** < **3cNa<sub>2</sub>** < **3dNa<sub>2</sub>**. They also show that these dianions are all sufficiently basic to promote the  $\alpha$ -metalation of the bromophenylacetic acids under investigation, albeit by different degrees.<sup>36</sup>

Through an appropriate balance between its reducing and basic properties, **3aNa<sub>2</sub>** appears to be the ideal candidate to achieve the chemoselective generation of the enediolates of bromophenylacetic acids. As a matter of fact, by employing **3aNa<sub>2</sub>** as the reagent of choice, we were able to accomplish the  $\alpha$ -alkylation of bromophenylacetic acids **5e** and **5f** under relatively mild reaction conditions, as illustrated in Scheme 5.

## Conclusions

Theoretical calculations and electrochemical analysis of the voltammetric reduction of the parent alkenes allowed us to set up a relative scale for the reducing strength of delocalized dianions. Inclusion of the solvent effect in the calculations improved the correlation between calculations and electrochemical results very significantly. These results nicely confirm and extend our original hypothesis that within a family of compounds the less delocalized dianions are the most powerful

reducing agents. This analysis was validated by studying the reactivity of 1,2-dipyridyl-1,2-disodioethanes towards halogenated benzoic and arylacetic acids. In full agreement with the predictions, diorganometal **3aNa<sub>2</sub>** displays an appropriate balance between its reducing and basic properties, which allowed us to use it as a selective base for the successful  $\alpha$ -alkylation of bromo-substituted arylacetic acids.

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calculations, and 0.999 for those with the PCM solvent, in agreement with what already reported for different classes of organic compounds.<sup>34</sup> However, extension of such an approach to the SOMO energies (Table S2, ESI†) do not show a good correlation with respect to the difference  $E_2^o - E_1^o$ , with  $r^2$  values for both *in vacuo* and PCM solvent calculations of 0.385 and 0.678, respectively. Accordingly, these data strongly suggest that the electron affinity is a better index for reduction potential predictions involving dianions.

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