

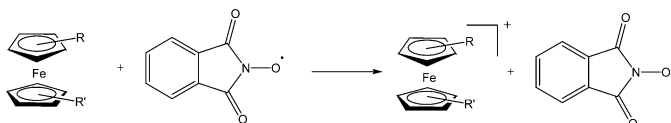
## A Kinetic Study of the Electron-Transfer Reaction of the Phthalimide-*N*-oxyl Radical (PINO) with Ferrocenes

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A kinetic study of the one-electron oxidation of a series of ferrocenes (FcX: X = H, CO<sub>2</sub>Et, CONH<sub>2</sub>, CH<sub>2</sub>CN, CH<sub>2</sub>OH, Et, and Me<sub>2</sub>) by PINO generated in CH<sub>3</sub>CN by reaction of *N*-hydroxyphthalimide (NHPI) with the cumyloxyl radical produced by 355 nm laser flash photolysis of dicumyl peroxide has been carried out. Ferrocenium cations were formed, and the reaction rate was determined by following the decay of PINO radical at 380 nm as a function of the FcX concentration. Rate constants were very sensitive to the oxidation potential of the substrates and exhibited a good fit with the Marcus equation, from which a  $\lambda$  value of 38.3 kcal mol<sup>-1</sup> was calculated for the reorganization energy required in the PINO/ferrocenes electron-transfer process. Knowing the ferrocene/ferrocenium self-exchange reorganization energy it was possible to calculate a value of 49.1 kcal mol<sup>-1</sup> for the PINO/PINO<sup>-</sup> self-exchange reaction in CH<sub>3</sub>CN. Moreover, from the Marcus cross relation and the self-exchange rates of ferrocene and dimethylferrocene, the intrinsic reactivity of PINO in electron-transfer reactions has been calculated as 7.6 × 10<sup>2</sup> M<sup>-1</sup> s<sup>-1</sup>. The implications of these values and the comparison with the electron-transfer self-exchange reorganization energies of peroxy radicals are briefly discussed.

### Introduction

The reactivity of phthalimide-*N*-oxyl radical (PINO) is receiving continuous attention since this species is the active oxidant in the synthetically useful metal-catalyzed oxidation of aliphatic and alkylaromatic hydrocarbons by *N*-hydroxyphthalimide (NHPI).<sup>1</sup> Moreover, the reactivity of PINO toward phenolic O–H bonds<sup>2,3</sup> represents an additional reason of interest since it may make PINO suitable for evaluating the radical-scavenging ability of phenolic antioxidants. In this respect it can be also noted that PINO may be a good model to mimic the properties of alkylperoxy radicals in hydrogen atom transfer (HAT) reactions. Accordingly, the bond dissociation energy (BDE) of the O–H bond formed by PINO in HAT reactions (88 kcal/mol)<sup>3</sup> is very close to that of the O–H bonds formed by alkylperoxy radicals.<sup>4</sup>

Generally, the HAT mechanism is the most common one when PINO reacts with C–H<sup>5</sup> and phenolic O–H bonds.<sup>2,6</sup> Recently, however, we have provided convincing evidence that the efficient *N*-demethylation of *N,N*-dimethylanilines promoted by PINO occurs by an electron-transfer (ET) mechanism.<sup>7</sup> It

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was suggested that an *N,N*-dimethylaniline radical cation is first formed that then undergoes proton loss from a C–H bond of the dimethylamino group. The kinetic data fitted a Marcus plot, but since the self-exchange ET reorganization energy of *N,N*-dimethylaniline is not known with certainty, only a lower limit ( $\geq 60$  kcal/mol) could be estimated for the reorganization energy of the PINO/PINO<sup>−</sup> self-exchange reaction.<sup>8</sup>

To confirm and quantitatively assess the properties of PINO in ET reactions is certainly important in view of the growing attention for the possible role of electron-transfer mechanisms in radical-scavenging reactions of phenolic antioxidants,<sup>10</sup> as well as for a better understanding of the catalytic role of this species in synthetically useful processes. Thus, we have considered it worthwhile to acquire definitive and unambiguous information on the self-exchange intrinsic barrier for the PINO/PINO<sup>−</sup> couple, by investigating the reactivity of PINO in the oxidation of a series of ferrocenes (**1–9**) to the corresponding ferrocenium cations, a *genuine* electron-transfer reaction.<sup>11</sup> Since the intrinsic barrier for the ferrocene/ferrocenium couple is known,<sup>12</sup> the Marcus cross relation should allow us to determine a reliable self-exchange ET intrinsic barrier for the PINO/PINO<sup>−</sup> couple. In this respect, it should also be mentioned that no information of this kind is presently available for nitroxyl radicals, even though the electron-transfer reductions of several stable dialkyl nitroxides have been qualitatively studied by using a series of reducing agents such as nitroarene radical anions,

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(6) Actually, with phenolic O–H bonds a proton-coupled electron-transfer mechanism has also been suggested.

(7) Baciocchi, E.; Bietti, M.; Gerini, M. F.; Lanzalunga, O. *J. Org. Chem.* **2005**, *70*, 5144–5149.

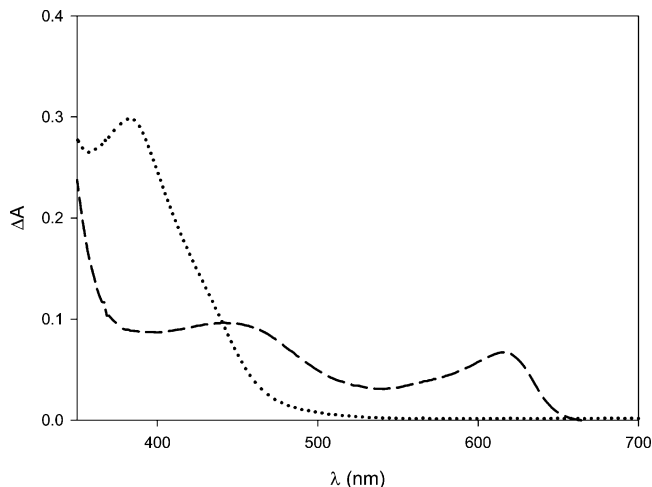
(8) This lower limit was determined from a  $\lambda = 37.6$  kcal mol<sup>−1</sup> for the ET process from *N,N*-dimethylanilines to PINO considering that the reorganization energy for the DMA<sup>+/•</sup>/DMA self-exchange reaction is <15 kcal mol<sup>−1</sup>.<sup>9</sup>

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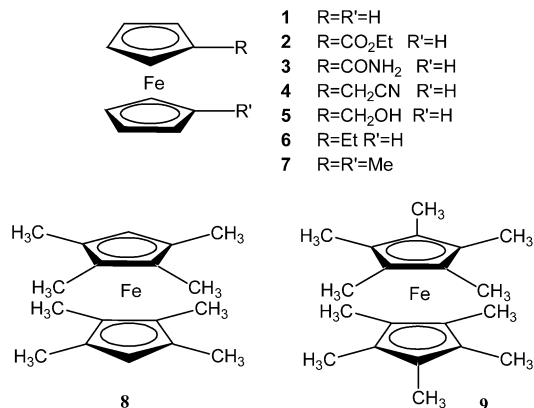
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**FIGURE 1.** UV–vis spectra of a CH<sub>3</sub>CN solution containing Pb(OAc)<sub>4</sub> (0.1 mM) and NHPI (3 mM) in the presence of 1% (v/v) AcOH at 25 °C in the absence (dotted line) or in the presence (dashed line) of ferrocene (**1**) (1 mM).

semiquinones, viologens, and  $\alpha$ -hydroxyl carbon-centered radicals.<sup>13</sup> The results of this study are presented herewith.



## Results

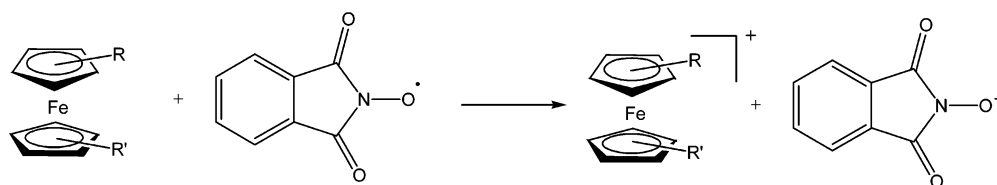
The ability of the phthalimide-*N*-oxyl radical to oxidize the ferrocene derivatives to the corresponding ferrocenium cations was first assessed spectrophotometrically by generating the PINO radical in CH<sub>3</sub>CN by reaction of NHPI with Pb(OAc)<sub>4</sub>, as previously described.<sup>2,5</sup> With ferrocenes **1–9** it was observed that when a solution of the ferrocene was added to a solution of PINO, the absorption of PINO ( $\lambda_{\text{MAX}} = 380$  nm) disappeared and was immediately replaced by that of the ferrocenium cations (**1<sup>+</sup>–9<sup>+</sup>**) characterized by absorption maxima in the 600–800 nm region of the spectrum<sup>14</sup> (see Figure 1 for the addition of **1** and Figures S1–S8 in the Supporting Information for the addition of ferrocenes **2–9**).

Thus, the electron-transfer reaction of PINO with ferrocenes occurs as reported in Scheme 1.

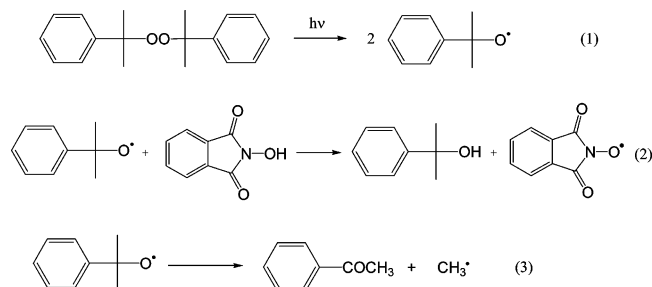
(13) Nigam, S.; Asmus, K.-D.; Willson, R. *J. Chem. Soc. Faraday I* **1976**, *72*, 2324–2340. Sealy, R. C.; Swartz, H. M.; Olive, P. L. *Biochem. Biophys. Res. Commun.* **1978**, *82*, 680–684. O'Neill, P.; Jenkins, T. C. *Faraday Discuss.* **1979**, 1912–1918.

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## SCHEME 1



## SCHEME 2



Since the process was too fast to be followed by conventional spectrophotometry, the reactions were kinetically investigated by the laser flash photolysis technique, where PINO was produced by hydrogen atom abstraction from *N*-hydroxyphthalimide (NHPI) by photochemically generated alkoxy radicals.<sup>3,7,15</sup> In the present study the hydrogen-abstrating species was the cumyloxy radical, generated by 355 nm laser flash photolysis of dicumyl peroxide (eqs 1 and 2 in Scheme 2).

The time-resolved spectra obtained in a LFP experiment carried out with a solution of dicumyl peroxide (0.9 M) and NHPI (4.5 mM) are reported in Figure 2, where it can be observed that the cumyloxy radical, characterized by an absorption maximum at 490 nm (empty circles),<sup>16</sup> undergoes a first-order decay accompanied by a corresponding buildup of optical density at  $\lambda_{\text{MAX}} = 380$  nm due to the absorption of the PINO radical (filled circles).<sup>5</sup> An isosbestic point can be identified at  $\lambda = 420$  nm.

Using the absorption maximum at 490 nm of cumyloxy radical, it was also possible to measure the hydrogen atom transfer rate ( $k_{\text{H}}$ ) from NHPI to the alkoxy radical itself that occurs in competition with its  $\beta$ -scission, leading to the formation of acetophenone and a methyl radical (eq 3 in Scheme 2,  $k_{\beta} \approx 6.5 \times 10^5 \text{ s}^{-1}$  in  $\text{CH}_3\text{CN}$ <sup>17</sup>).  $k_{\text{H}}$  was measured by following the decrease of the optical density at 490 nm, as a function of the concentration of NHPI in the range 2–13 mM. Clean first-order decays were observed, and a linear dependency of the observed rates ( $k_{\text{obs}}$ ) on the concentration of NHPI was obtained (see Figure S9 in the Supporting Information). From the slope of the plot of  $k_{\text{obs}}$  vs the NHPI concentration the second-order rate constant for this process was determined as  $5.1 \times 10^7 \text{ M}^{-1} \text{ s}^{-1}$ . This value, which represents the first direct determination of the rate constant for the HAT process from NHPI to a *tert*-alkoxy radical, is much lower than that ( $k = 1.05 \times 10^9 \text{ M}^{-1} \text{ s}^{-1}$ ) indirectly determined in benzene by using the thermal decomposition of dicumylhyponitrite at 30 °C.<sup>15,18</sup>

(15) Coseri, S.; Mendenhall, G. D.; Ingold, K. U. *J. Org. Chem.* **2005**, *70*, 4629–4636.

(16) Avila, D. V.; Luszyk, J.; Ingold, K. U. *J. Am. Chem. Soc.* **1992**, *114*, 6576–6577. Avila, D. V.; Ingold, K. U.; Di Nardo, A. A.; Zerbetto, F.; Zgierski, M. Z.; Luszyk, J. *J. Am. Chem. Soc.* **1995**, *117*, 2711–2718.

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This difference can be easily explained by the hypothesis of Ingold and associates,<sup>19</sup> according to which for a reaction of the type  $\text{XH} + \text{Y}^{\bullet}$  the rate decreases as the hydrogen bond accepting ability of the solvent (measured by Abraham's  $\beta_2^{\text{H}}$  values<sup>20</sup>) increases. Thus, the rate of the HAT reaction between cumyloxy radical and NHPI is expected to be much lower in  $\text{CH}_3\text{CN}$  than in benzene since the former is a much better hydrogen bond accepting solvent ( $\beta_2^{\text{H}} = 0.44$ ) than the latter ( $\beta_2^{\text{H}} = 0.14$ ).

The PINO signal is stable on the millisecond time scale (Figure 3a,  $\lambda = 380$  nm), but in the presence of an excess of ferrocene (0.2 mM), a fast decay occurs that follows first-order kinetics (Figure 3b for the case of **1**, from the first-order fit  $k_{\text{obs}} = 4.0 \times 10^3 \text{ s}^{-1}$ ). A significant residual absorption at 380 nm was however observed, likely due to the formation of  $\text{PINO}^-$  following the ET from **1** to  $\text{PINO}^{\bullet}$ . Accordingly, when the experiment was carried out in the presence of AcOH (0.2% v/v), a large reduction of the residual absorption took place,<sup>22</sup> without significant change in the PINO decay rate (Figure 3c, from the first-order fit  $k_{\text{obs}} = 3.8 \times 10^3 \text{ s}^{-1}$ ).<sup>23</sup>

In Figure 4 are reported the time-resolved spectra obtained after 355 nm LFP of an  $\text{N}_2$ -saturated  $\text{CH}_3\text{CN}$  solution containing dicumyl peroxide (0.9 M), NHPI (4.5 mM), and **1** (0.1 mM) in the presence of 0.2% (v/v) AcOH, at  $T = 25$  °C. The absorption spectrum of the PINO radical, recorded 10.5  $\mu\text{s}$  after the laser pulse (filled circles), undergoes a first-order decay (see inset a) accompanied by the formation of the ferrocenium ion (**1**<sup>+</sup>) (inset b), which displays the characteristic visible absorption band at  $\lambda_{\text{MAX}} = 620$  nm.<sup>14</sup> Two isosbestic points can be identified at ca.  $\lambda = 350$  nm and  $\lambda = 470$  nm. Similar results were obtained for ferrocenes **3–7**, and the corresponding time-resolved spectra are reported in Figures S12–S16 in the Supporting Information. Ferrocene **2** exhibited too low a reactivity for the PINO decay to be followed in the microsecond time scale, and it was not possible to study the reactivity of PINO with the more oxidizable ferrocenes **8** and **9** ( $E^{\circ} = -0.02$  and  $-0.1$  V vs SCE, respectively; see Experimental Section) since the decay of the cumyloxy radical was significantly accelerated by the presence

(18) By using the 355 nm laser it was possible to measure the hydrogen atom transfer rate ( $k_{\text{H}}$ ) from NHPI to the cumyloxy radical by the LFP approach also in benzene. The value obtained by us following the decay of cumyloxy radical, as a function of the concentration of NHPI in the range 0.1–0.5 mM at 25 °C ( $k = 1.08 \times 10^9 \text{ M}^{-1} \text{ s}^{-1}$ , see Figure S10 in the Supporting Information) is in excellent agreement with the value determined by Coseri and Ingold by thermal decomposition of dicumylhyponitrite at 30 °C.<sup>15</sup>

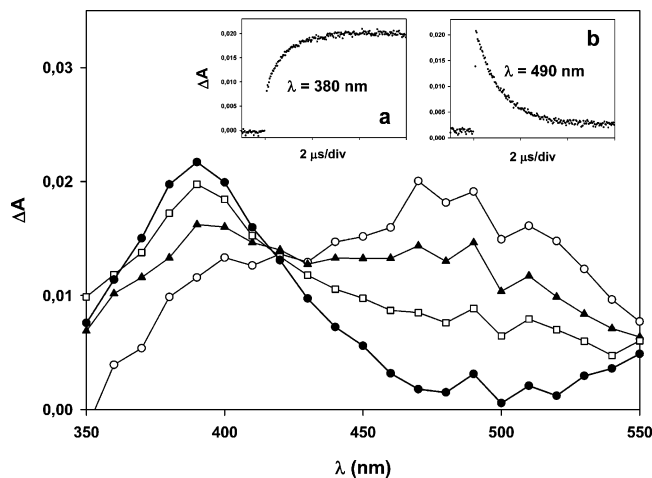
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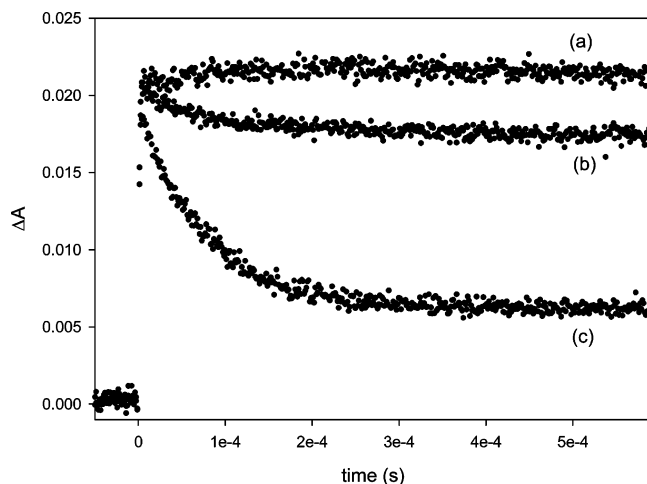
(21) The absorption spectrum of this species produced by reaction of NHPI with triethylamine is reported in Figure S11 in the Supporting Information.

(22) In the presence of AcOH the residual absorption at 380 nm is likely due to the formation of the ferrocenium ion.

(23) No significant kinetic effect on the decay rate of PINO was observed also in the presence of 1% AcOH.



**FIGURE 2.** Transient absorption spectra measured 160 ns (empty circles), 510 ns (filled circles), 1.2  $\mu\text{s}$  (empty squares), and 4.0  $\mu\text{s}$  (filled triangles) after 355 nm laser excitation of a solution of dicumyl peroxide (0.9 M) and NHPI (4.5 mM) in  $\text{CH}_3\text{CN}$  at 25  $^\circ\text{C}$  under  $\text{N}_2$ . Inset a: first-order buildup of the absorption of the PINO radical at 380 nm. Inset b: first-order decay of the absorption of the cumyloxy radical at 490 nm.

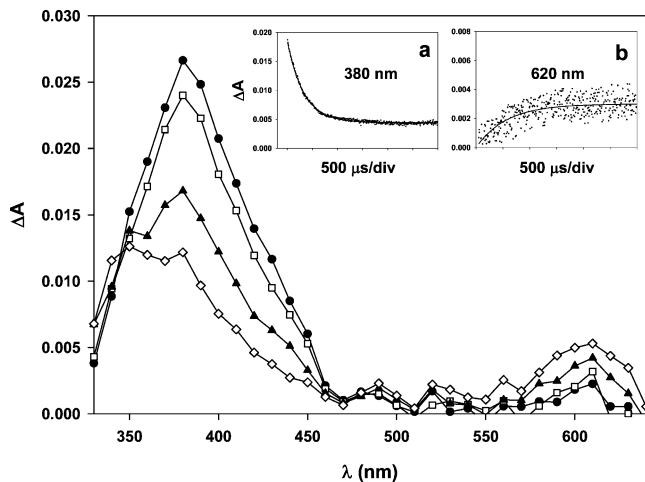


**FIGURE 3.** (a) Time-resolved changes in absorbance measured at 380 nm after laser excitation of a solution of dicumyl peroxide (0.9 M) and NHPI (4.5 mM) in  $\text{CH}_3\text{CN}$  (b) in the presence of ferrocene (**1**) (0.2 mM) and (c) in the presence of **1** (0.2 mM) and 0.2% AcOH (v/v).

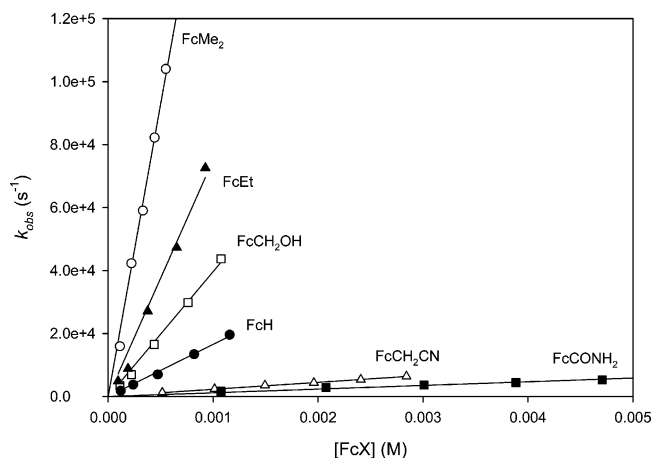
of these ferrocenes, with the reaction occurring, under the experimental conditions employed, at a rate comparable to that observed for the reaction of the cumyloxy radical with NHPI.<sup>24</sup>

When the pseudo-first-order rate constants ( $k_{\text{obs}}$ ) for the decay of the PINO radical measured at 380 nm were plotted against the concentration of ferrocenes **1** and **3–7**, excellent linear dependencies were observed (Figure 5), and the second-order rate constants ( $k_{\text{et}}$ ) for the one-electron oxidation of compounds **1** and **3–7** with PINO were obtained from the slopes of these plots. For the reasons mentioned above only an upper limit rate constant ( $k_{\text{et}} < 10^5 \text{ M}^{-1} \text{ s}^{-1}$ ) is reported for the reaction of **2** (the least oxidizable among the ferrocenes investigated) with PINO. All the kinetic data are collected in Table 1. In the same

(24) Further studies are underway in our laboratory in order to quantitatively determine the reactivity of *tert*-alkoxy radicals in the reaction with easily oxidizable ferrocenes.



**FIGURE 4.** Time-resolved absorption spectra observed after 355 nm LFP of an  $\text{N}_2$ -saturated  $\text{CH}_3\text{CN}$  solution ( $T = 25 \text{ }^\circ\text{C}$ ) containing dicumyl peroxide (0.9 M), NHPI (4.5 mM), and ferrocene (**1**) (0.1 mM) in the presence of 0.2% (v/v) AcOH, at 10.5  $\mu\text{s}$  (filled circles), 100  $\mu\text{s}$  (empty squares), 500  $\mu\text{s}$  (filled triangles), and 1.1 ms (empty diamonds) after the 20 ns, 20 mJ laser flash. Inset a: first-order decay of the absorption of the PINO radical at 380 nm. Inset b: first-order buildup of the absorption of the ferrocenium ion at 620 nm.



**FIGURE 5.** Dependence of  $k_{\text{obs}}$  for decay of PINO on the concentrations of ferrocenes **1** and **3–7** in  $\text{CH}_3\text{CN}$  at 25  $^\circ\text{C}$ .

table are also displayed the redox potentials of the ferrocenes **1–7** measured by cyclic voltammetry (see Experimental Section) and the electron-transfer free energies  $\Delta G^{\circ}_{\text{et}}$ . For the calculation of the latter values an  $E^{\circ}$  value of 0.69 V vs SCE for the PINO/PINO<sup>-</sup> couple was used, measured in  $\text{CH}_3\text{CN}$ .<sup>25</sup>

## Discussion

The data in Table 1 show that the second-order rate constants for the electron transfer from compounds **1–7** to PINO ( $k_{\text{et}}$ ) are very sensitive to the oxidation potential of the substrate, increasing with decreasing  $E^{\circ}$  value, i.e., as the free energy change of the electron-transfer step ( $\Delta G^{\circ}_{\text{et}}$ ) decreases. A quantitative assessment of this dependence can be obtained by treating the data according to eq 1, which combines the Eyring

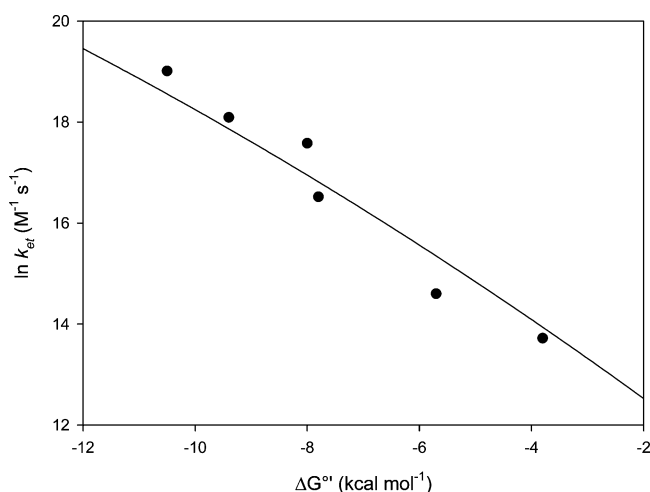
(25) A value 0.84 V vs SCE has been recently reported.<sup>26</sup> However, we have preferred to use the value measured by us that is coincident with that previously measured by Einhorn et al.<sup>27</sup>



**TABLE 1.** Second-Order Rate Constants and Electron-Transfer Free Energies for the Reaction of Ferrocenes 1–7 with PINO in CH<sub>3</sub>CN at 25 °C<sup>a</sup> and Oxidation Potentials of Ferrocenes 1–7

substrate	$E^{\circ b}$	$\Delta G_{\text{et}}^{\circ c}$	$k_{\text{et}} (\text{M}^{-1} \text{s}^{-1})^d$
<b>1</b>	0.41	−6.5	$(1.5 \pm 0.1) \times 10^7$ $(1.6 \pm 0.1) \times 10^7 e$
<b>2</b>	0.65	−0.9	$< 10^5$
<b>3</b>	0.58	−2.5	$(9.1 \pm 0.7) \times 10^5$
<b>4</b>	0.50	−4.4	$(2.2 \pm 0.1) \times 10^6$
<b>5</b>	0.40	−6.7	$(4.3 \pm 0.3) \times 10^7$
<b>6</b>	0.34	−8.1	$(7.2 \pm 0.3) \times 10^7$
<b>7</b>	0.29	−9.2	$(1.8 \pm 0.1) \times 10^8$ $(1.7 \pm 0.1) \times 10^8 e$

<sup>a</sup> Dicumyl peroxide (0.9 M), NHPI (4.5 mM), ferrocenes (0.1–4.7 mM) in the presence of 0.2% (v/v) AcOH. <sup>b</sup>V vs SCE in CH<sub>3</sub>CN. <sup>c</sup>In kcal mol<sup>−1</sup>, on the basis of an  $E^{\circ}_{\text{red}}$  value of 0.69 V vs SCE for PINO (see text). <sup>d</sup>Determined from the slopes of the  $k_{\text{obs}}$  (for decay of PINO radical, monitored at 380 nm) vs ferrocene concentration (see Figure 5). <sup>e</sup>In the absence of AcOH.

**FIGURE 6.** Diagram of  $\ln k_{\text{et}}$  vs  $\Delta G^{\circ'}$  for the reactions of ferrocenes **1** and **3–7** with PINO. The solid circles correspond to the experimental values; the curve is calculated by nonlinear least-squares fit to eq 1 with  $Z = 6 \times 10^{11} \text{ M}^{-1} \text{ s}^{-1}$ .

and Marcus equations.<sup>28,29</sup> In eq 1,  $\Delta G^{\circ'}$  is the standard free energy for the electron-transfer step corrected for the electrostatic interaction arising from the charge variation in the reactants upon electron transfer,  $\lambda$  is the reorganization energy, and  $Z$  is the bimolecular collision frequency. The satisfactory fit ( $r^2 = 0.927$ ) obtained when the  $\ln k_{\text{et}}$  values are plotted against the  $\Delta G^{\circ'}$  values is shown in Figure 6. (See Supporting Information for the calculation details.)

$$k_{\text{et}} = Z e^{-(\lambda + \Delta G^{\circ'})^2 / 4\lambda RT} \quad (1)$$

From the nonlinear least-squares fitting, a  $\lambda$  value of 38.3 kcal mol<sup>−1</sup> can be calculated for the reorganization energy required in the transfer of one electron from ferrocene derivatives to PINO. For this fit, the frequency factor  $Z$  was taken as  $6 \times 10^{11} \text{ M}^{-1} \text{ s}^{-1}$ , as suggested for reactions in solution.<sup>29</sup> The

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(28) Marcus, R. A. *Ann. Rev. Phys. Chem.* **1964**, *15*, 155.

(29) Ebersson, L. *Electron Transfer Reactions in Organic Chemistry*; Springer Verlag: Berlin, 1986; Chapter 3.

good quality of the fit indicates that the ferrocenes investigated should have very close self-exchange reorganization energies, and in agreement Wahl et al.<sup>12</sup> state that ring substituents affect the rates of ferrocene self-exchange only to a moderate extent.<sup>30</sup> Thus, assuming that the value (27.5 kcal mol<sup>−1</sup> in CH<sub>3</sub>CN)<sup>31</sup> of the ET self-exchange reorganization energy for the ferrocene/ferrocenium couple ( $\lambda_{\text{Fc}^+/\text{Fc}}$ ) holds, at least to a first approximation, also for the substituted ferrocenes, the reorganization energy for the PINO/PINO<sup>−</sup> couple ( $\lambda_{\text{PINO}/\text{PINO}^-}$ ) can be calculated from eq 2 as 49.1 kcal mol<sup>−1</sup>.

$$1/2(\lambda_{\text{PINO}/\text{PINO}^-} + \lambda_{\text{Fc}^+/\text{Fc}}) = 38.3 \quad (2)$$

Using the Marcus cross relation given in eq 3, the ET self-exchange rate constant of the PINO/PINO<sup>−</sup> couple ( $k_{\text{ex}}$ ) can also be calculated. In eq 3,  $k_{\text{et}}$  is the rate of the cross reaction,  $k_{\text{ex}}'$  is the self-exchange ET rate constant of the specific ferrocene/ferrocenium couple (known for compounds **1** and **7**),<sup>12</sup>  $K_{\text{et}}$  is the equilibrium constant for the appropriate electron-transfer process (calculated from the difference in reduction potential between PINO and **1** or **7**), and  $f$  is a correction factor generally assumed to be 1.<sup>32</sup>

$$k_{\text{ex}} = \frac{k_{\text{et}}^2}{k_{\text{ex}}' K_{\text{et}} f} \quad (3)$$

From the  $k_{\text{et}}$  values for the reaction of PINO with ferrocenes **1** and **7** (Table 1), very close values of  $k_{\text{ex}}$ ,  $8.6 \times 10^2$  and  $6.6 \times 10^2 \text{ M}^{-1} \text{ s}^{-1}$ , respectively, for the PINO/PINO<sup>−</sup> couple can be obtained. The average value,  $7.6 \times 10^2 \text{ M}^{-1} \text{ s}^{-1}$  can be taken as the *intrinsic* reactivity of PINO in electron-transfer reactions. From this value, a  $\lambda_{\text{PINO}/\text{PINO}^-}$  value of 48.5 kcal mol<sup>−1</sup> can be calculated, which is in excellent agreement with the value of 49.1 kcal/mol determined from the nonlinear least-squares fit of Figure 6.

Even though the good quality of the fit in Figure 6 as well as the fact that the Marcus cross relation provides us with very close values of  $k_{\text{ex}}$  for the PINO/PINO<sup>−</sup> couple by using two different ferrocenes would indicate that the system under investigation exhibits substantial adiabatic behavior, it is important to mention that Wahl et al.<sup>12</sup> have also suggested that ferrocene self-exchange reactions might have some nonadiabatic character.<sup>33</sup> This suggestion appears corroborated by Weaver and associates,<sup>34</sup> who have estimated a value of 0.1 kcal mol<sup>−1</sup> for the electronic matrix coupling element ( $H_{\text{ab}}$ )<sup>35</sup> of the ferrocene/ferrocenium self-exchange reaction, somewhat low to

(30) The largest deviations concern decamethylferrocene on one side and ferrocene substituted by a charged quaternary amino group on the other side, whereas very close values of self-exchange rate are instead observed for ferrocene, 1,1'-dimethylferrocene, di-*n*-butylferrocene, and methyl ferrocenecarboxylate. Moreover similar self-exchange reorganization energies have been reported for ferrocene, chloromercuriferrocene, butylferrocene, and 1,1'-dimethylferrocene. Pladziewicz, J. R.; Espenson, J. H. *J. Am. Chem. Soc.* **1973**, *95*, 56. Ebersson, L.; Barry, J. E.; Finkelstein, M.; Moore, W. M.; Ross, S. D. *Acta Chem. Scand.* **1986**, *B40*, 283–294.

(31) This value is obtained by the self-exchange rate for the Fc/Fc<sup>+</sup> couple in MeCN at 25 °C ( $5.3 \times 10^6 \text{ M}^{-1} \text{ s}^{-1}$ ) reported in ref 12, however using  $Z = 6 \times 10^{11} \text{ M}^{-1} \text{ s}^{-1}$ , as for the fit above.

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(33) We thank one of the referees for calling our attention to this point.

(34) Mc Manis, G. E.; Nielson, R. M.; Gochev, A.; Weaver, M. J. *J. Am. Chem. Soc.* **1989**, *111*, 5533–5534.

(35)  $H_{\text{ab}}$  describes the extent of overlap between the donor and acceptor redox orbitals, which determines the extent of resonance splitting of the barrier tops.

ensure adiabatic behaviors.<sup>36</sup> Certainly, this a very important problem that should deserve both specific experimental and theoretical investigations; nevertheless a possible degree of nonadiabaticity of ferrocene self-exchange reactions should not significantly influence our results (particularly the self-exchange electron-transfer rate obtained for the PINO/PINO<sup>-</sup> couple),<sup>39</sup> as Nelsen and Pladziewicz have recently reported a very large number of data showing that the Marcus cross relation remains valid also when applied to couples with  $H_{ab}$  as small as 0.01 kcal mol<sup>-1</sup>.<sup>41</sup>

The  $\lambda_{\text{PINO/PINO}^{\cdot}}$  value of 49.1 kcal mol<sup>-1</sup>, calculated above, is significantly lower than that (>60 kcal mol<sup>-1</sup>) estimated in our study of the PINO-promoted *N*-demethylation of *N,N*-dimethylanilines.<sup>7</sup> We have no doubt that the value reported herewith is the most reliable one. As already mentioned, the self-exchange reorganization energy for the ArNMe<sub>2</sub>/ArNMe<sub>2</sub><sup>+</sup> couple is not known with certainty, and moreover the PINO-promoted *N*-demethylation reaction is a two-step reaction: A reversible electron transfer from the *N,N*-dimethylaniline to PINO followed by deprotonation of the anilinium radical cation. Thus, it cannot be excluded that with the less electron-rich substrates rates might be somewhat influenced by the second step involving the deprotonation of the *N,N*-dimethylaniline radical cation.

Interestingly, our  $\lambda_{\text{PINO/PINO}^{\cdot}}$  value is very close to the value determined by Espenson and his associates for the self-exchange hydrogen atom transfer reaction of the same species ( $\lambda_{\text{PINO/NHPI}} = 49$  kcal/mol<sup>-1</sup>).<sup>42</sup> Similar intrinsic barriers for self-exchange ET and HAT reactions have been observed for other systems<sup>43</sup> and have been explained by suggesting that in HAT reactions the larger inner-sphere reorganization energy associated with O–H bond cleavage may be partially offset by the absence of solvent reorganization energy. The latter is instead present in ET processes. Anyway, whatever the explanation, an important conclusion is that for PINO the choice between exhibiting ET or HAT reactivity should be principally dictated by thermodynamics.

Since PINO and peroxy radicals have similar reduction potentials,<sup>44</sup> it would be also of great interest to compare the self-exchange electron-transfer reorganization energy of these species in order to establish if and to what extent PINO can be

a model of peroxy radicals also in electron-transfer reactions. Unfortunately, examination of the literature provided us with very discordant data for the self-exchange electron-transfer reorganization energies of peroxy radicals ( $\lambda_{\text{ROO}^{\cdot}/\text{ROO}^{\cdot}}$ ). Thus, Fukuzumi et al.<sup>37</sup> have recently reported a very high  $\lambda_{\text{ROO}^{\cdot}/\text{ROO}^{\cdot}}$  value (185–189 kcal mol<sup>-1</sup>) for cumylperoxy radical in EtCN, a value that is extremely different than that measured by us for PINO in CH<sub>3</sub>CN (49.1 kcal mol<sup>-1</sup>). However, much lower  $\lambda_{\text{ROO}^{\cdot}/\text{ROO}^{\cdot}}$  values, not much different from that of PINO, are reported for other alkylperoxy radicals, albeit under different conditions. Accordingly, a value of 72 kcal mol<sup>-1</sup> has been reported by Jovanovic et al.<sup>38</sup> for  $\lambda_{\text{ROO}^{\cdot}/\text{ROO}^{\cdot}}$  of methylperoxy, cyclohexylperoxy, and (dimethyl)hydroxyethylperoxy radicals. Moreover,  $\lambda_{\text{ROO}^{\cdot}/\text{ROO}^{\cdot}}$  values in the 60–70 kcal mol<sup>-1</sup> range can be calculated from an estimate of  $40 \pm 4$  kcal mol<sup>-1</sup> for the reorganization energy for ET reactions between closed-shell organics and several alkyl peroxy radicals.<sup>45,46</sup> Another estimate for  $\lambda_{\text{ROO}^{\cdot}/\text{ROO}^{\cdot}}$  ( $\geq 45$  kcal mol<sup>-1</sup>) is possible from the rate constant ( $2.1 \times 10^6$  M<sup>-1</sup> s<sup>-1</sup>) for the reaction of *N,N*-dimethylaniline with *t*-BuOO<sup>•</sup> reported by Das et al.<sup>47,48</sup> Although the above values are obtained in water, still lower values are probably to be expected in CH<sub>3</sub>CN and EtCN since the solvent reorganization energy accompanying the electron transfer should be larger in water than in a less polar solvent.<sup>29</sup> Furthermore, it is likely that in aqueous solvents electron transfer is concerted with proton transfer,<sup>49</sup> and this should lead to a greater reorganization energy.<sup>50</sup>

In conclusion, given the uncertainty in the self-exchange ET reorganization energy value for the peroxy radicals,<sup>51</sup> a meaningful comparison of the intrinsic reactivity in ET processes of these radicals with that of PINO is not possible at present. Further studies, aimed at obtaining additional and, hopefully, definitive information on the electron-transfer reactivity of peroxy radicals, are in progress in our laboratories.

## Experimental Section

**Starting Materials.** CH<sub>3</sub>CN (spectrophotometric grade) was distilled over CaH<sub>2</sub>. Commercial samples of dicumyl peroxide and *N*-hydroxyphthalimide were used as received. Ferrocene FcH (**1**), ferroceneacetonitrile FcCH<sub>2</sub>CN (**4**), ferrocenemethanol FcCH<sub>2</sub>OH (**5**), ethylferrocene FcEt (**6**), 1,1'-dimethylferrocene FcMe<sub>2</sub> (**7**), octamethylferrocene (**8**), and decamethylferrocene (**9**) are commercially available and were further purified by sublimation (compounds **1**, **4**, **5**, **7**, **8**, and **9**) or by column chromatography on silica gel using toluene as eluent (compound **6**). Ethyl ferrocenecarboxylate, FcCO<sub>2</sub>Et (**2**), was prepared by esterification of

(36) It should also be noted that in ref 34 the value measured for the self-exchange rate of the ferrocene/ferrocenium couple ( $9 \times 10^6$  M<sup>-1</sup> s<sup>-1</sup>) is twice larger than that reported in ref 12. However, also using this value,  $\lambda_{\text{PINO/PINO}^{\cdot}}$  is 50.2 kcal mol<sup>-1</sup>, which is a value not significantly different from that in the text. For our calculations, we have preferred the value reported in ref 12, since this is the value used in previous studies to determine the reorganization energy for peroxy radicals (vide infra).<sup>37,38</sup>

(37) Fukuzumi, S.; Shimoosako, K.; Suenobu, T.; Watanabe, Y. *J. Am. Chem. Soc.* **2003**, *125*, 9074–9082.

(38) Jovanovic, S. V.; Jankovic, I.; Josimovic, L. *J. Am. Chem. Soc.* **1992**, *114*, 9018–9021.

(39) It should also be mentioned that very recently Mayer and his associates<sup>40</sup> have reported that there is not much difference between adiabatic and nonadiabatic reorganization energies for  $H_{ab}$  values around 0.028 kcal mol<sup>-1</sup>.

(40) Rhile, I. J.; Markle, T. F.; Nagao, H.; DiPasquale, A. G.; Lam, O. P.; Lockwood, M. A.; Rotter, K.; Mayer, J. M. *J. Am. Chem. Soc.* **2006**, *128*, 6075–6088.

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(42) Cai, Y.; Koshino, N.; Saha, B.; Espenson, J. H. *J. Org. Chem.* **2005**, *70*, 238–243.

(43) Roth, J. P.; Lovell, S.; Mayer, J. M. *J. Am. Chem. Soc.* **2000**, *122*, 5486–5498.

(44) For example, the reduction potential of cumylperoxy radical (0.65 V vs SCE in CH<sub>3</sub>CN)<sup>37</sup> is almost identical to that of PINO.

(45) Jonsson, M. *J. Phys. Chem. A* **1996**, *100*, 6814–6818.

(46) Self-exchange ET energies for most closed-shell organics lie between 10 and 20 kcal mol<sup>-1</sup>; see: Ebersson, L. *Electron Transfer Reactions in Organic Chemistry*; Springer-Verlag: Berlin, 1986; Chapter 4, Table 5.

(47) Das, T. D. A.; Dhanasekaran, T.; Alfassi, Z. B.; Neta, P. *J. Phys. Chem. A* **1998**, *102*, 280–284.

(48) Assuming that the self-exchange ET energy for *N,N*-dimethylaniline is  $\leq 15$  kcal mol<sup>-1</sup>.

(49) Neta, P.; Huie, R. E.; Maruthamuthu, P.; Steenken, S. *J. Phys. Chem.* **1989**, *93*, 7654–7659.

(50) Sjödin, M.; Styring, S.; Åkermark, B.; Sun, L.; Hammarström, L. *J. Am. Chem. Soc.* **2000**, *122*, 3932–3936. Rhile, I. J.; Mayer, J. M. *J. Am. Chem. Soc.* **2004**, *126*, 12718–12719. Costentin, C.; Evans, D. H.; Robert, M.; Savèant, J.-M.; Singh, P. S. *J. Am. Chem. Soc.* **2005**, *127*, 12490–12491. Sjödin, M.; Styring, S.; Wolpher, H.; Xu, Y.; Sun, L.; Hammarström, L. *J. Am. Chem. Soc.* **2005**, *127*, 3855–3863. Rhile, I. J.; Markle, T. F.; Nagao, H.; DiPasquale, A. G.; Lam, O. P.; Lockwood, M. A.; Rotter, K.; Mayer, J. M. *J. Am. Chem. Soc.* **2006**, *128*, 6075–6088.

(51) For the problems involved in the precise evaluation of  $\lambda_{\text{ROO}^{\cdot}/\text{ROO}^{\cdot}}$  values see ref 49.

commercially available ferrocenecarboxylic acid with ethanol according to the literature.<sup>52</sup> Ferrocene carbamide, FcCONH<sub>2</sub> (**3**), was prepared from the acyl chloride FcCOCl according to a literature procedure.<sup>53</sup>

**Cyclic Voltammetry.** Cyclic voltammetry at the steady disk electrode (glassy carbon disk, 1.5 mm in diameter) was carried out at 25 °C in CH<sub>3</sub>CN containing the ferrocenes **1–9** (2.0 mM) or NHPI (2.0) mM and Bu<sub>4</sub>NBF<sub>4</sub> (0.1 M) as supporting electrolyte. In the experiment with NHPI, in order to generate PINO<sup>-</sup>, collidine (4 mM) was added to the CH<sub>3</sub>CN solution. A three-electrode circuit was used with a homemade potentiostat with positive feedback ohmic drop compensation and PLI hardware (Vernier Software & Technology) controlled by a program written in C++ language for Windows 95/98. The auxiliary electrode was a platinum wire (surface 1 cm<sup>2</sup>), and an Ag/AgCl (KCl 3M) electrode was used as reference; the redox potential values are then referred to SCE. The sweep scan was 500 mV/s.

**Spectrophotometric Studies.** PINO was generated by the oxidation of NHPI (3 mM) with Pb(OAc)<sub>4</sub> (0.1 mM) in CH<sub>3</sub>CN at 25 °C under an argon atmosphere, and its UV–vis absorption spectrum was recorded ( $\lambda_{\text{MAX}} = 380$  nm). A solution of the substrate (**1–7**) was then added into the PINO solution in the cuvette (substrate concentration 1 mM). The absorption of PINO disappeared and was replaced by that of the ferrocenium cations.

**Laser Flash Photolysis Experiments.** Laser flash photolysis experiments were carried out with an Applied Photophysics LK-60 laser kinetic spectrometer providing 8 ns pulses, using the third harmonic (355 nm) of a Quantel Brilliant-B Q-switched Nd:YAG

laser. The laser energy was adjusted to  $\leq 10$  mJ/pulse by the use of the appropriate filter. A 3 mL Suprasil quartz cell (10 mm  $\times$  10 mm) was used for all the experiments. N<sub>2</sub>-saturated CH<sub>3</sub>CN solutions containing 0.2% (v/v) AcOH, dicumyl peroxide (0.9 M), *N*-hydroxyphthalimide (4.5 mM), and ferrocenes **1–7** (0.1–4.7 mM) were used. All the experiments were carried out at  $T = 25 \pm 0.5$  °C under magnetic stirring. Data were collected at individual wavelengths with an Agilent Infinium oscilloscope and analyzed with the kinetic package implemented in the instrument. Rate constants were obtained by monitoring the change of absorbance at 380 nm and by averaging 3–5 values. Each kinetic trace obeyed a first-order kinetic, and second-order rate constants were obtained from the slopes of the plots of the observed rate constants,  $k_{\text{obs}}$ , vs substrate concentration.

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**Supporting Information Available:** UV–vis absorption spectra of **1<sup>+</sup>–9<sup>+</sup>** (spectrophotometric studies), dependence of  $k_{\text{obs}}$  on [NHPI] for the HAT from NHPI by the cumyloxyl radical in CH<sub>3</sub>CN and benzene, UV–vis absorption spectrum of PINO<sup>-</sup>, time-resolved absorption spectra of the dicumyl peroxide/NHPI/**1, 3–7** systems (laser flash photolysis in N<sub>2</sub>-saturated CH<sub>3</sub>CN), determination of the reorganization energy. This material is available free of charge via the Internet at <http://pubs.acs.org>.

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