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Direct Experimental Evidence for Alkoxyl Radicals Reacting as Hydrogen Atom Donors toward Pyridines

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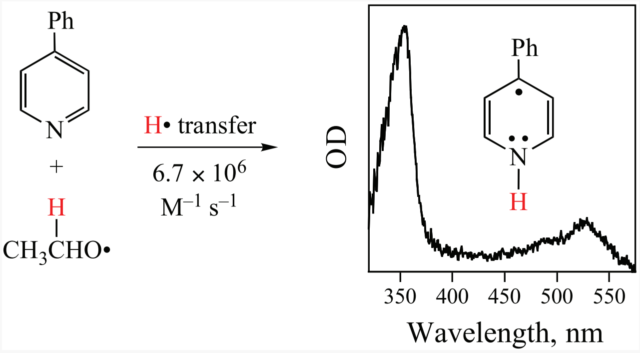
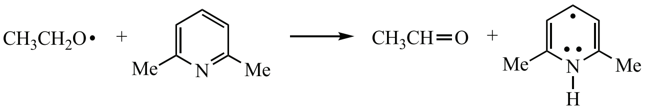
ABSTRACT: Nanosecond transient absorption spectroscopy was used to generate ethoxyl radicals and demonstrate that they react with 2,6-lutidine and 4-phenylpyridine to give the corresponding *N*-hydropyridinyl radicals—products of a novel hydrogen atom transfer from the alkoxyl radical to the nitrogen atom of the substituted pyridines. Nanosecond kinetics show that both reactions are rapid ($k \sim 10^7$ M^{-1} s^{-1}) in acetonitrile at room temperature. Rate constants measured for reaction of the ethoxyl vs. d_5-ethoxyl radical with 2,6-lutidine and 4-phenylpyridine show that both reactions exhibit primary H/D kinetic isotope effects for the hydrogen (deuterium) atom transfer reactions.

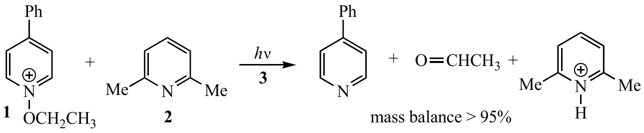


■ INTRODUCTION

The reactions of alkoxyl radicals form an important part of radical chemistry in many common organic,[1] biological,[2] and atmospheric[3] processes. Although alkoxyl radicals are perhaps most commonly recognized for their hydrogen atom abstracting ability[4] due to the relatively strong O−H bond that is formed, they also participate in a variety of other reactions, including unimolecular fragmentations,[5] additions to unsaturated compounds,[6] and isomerizations.[7] Disproportionation reactions of primary and secondary alkoxyl radicals, forming the corresponding alcohols and carbonyl compounds, are known in both solution and the gas phase.[8] Analogous reactions of alkoxyl radicals with other radicals (e.g., NO)[9] have also been well documented. A novel reaction of alkoxyl radicals containing a hydrogen on the carbon atom α to the oxygen-centered radical has recently been proposed wherein the alkoxyl radical acts as a hydrogen atom donor to pyridine derivatives (see below).[10] These reactions appear to the first reported examples of alkoxyl radicals behaving as hydrogen atom donors with closed-shell molecules.



The hydrogen atom transfer (HAT) between alkoxyl radicals and pyridines was proposed as a propagation step in the photochemically sensitized chain decomposition of *N*-alkoxylpyridinium salts.[10] For example, the reaction of *N*-ethoxy-4-phenylpyridinium hexafluorophosphate (**1**) with 2,6-lutidine (**2**) photosensitized by 2-chlorothioxanthone (**3**) proceeds via a chain reaction leading to the formation of 4-phenylpyridine, acetaldehyde, and 2,6-lutidinium hexafluorophosphate (see below). The reaction quantum yield approached ~100 at high [**2**]. Similar results were observed starting with other pyridinium salts.



The proposed chain mechanism for the photoreduction of the *N*-ethoxypyridinium cation starts with excitation of **3** to generate its singlet excited state (^{1}**3***) that subsequently undergoes rapid and efficient intersystem crossing to give its triplet excited state (^{3}**3***). One-electron reduction of **1** by ^{3}**3*** results in formation of the *N*-ethoxypyridinyl radical, which then undergoes rapid N−O bond scission ($k \sim 1 \times 10^{11}$ s^{-1}) to generate 4-phenylpyridine and the ethoxyl radical.[11] The ethoxyl radical so formed was proposed to react with **2** by HAT to form acetaldehyde and the *N*-hydro-2,6-lutidinyl radical (**2H**$^•$), as shown above. **2H**$^•$ then reduces **1** to give the 2,6-lutidinium cation (**2H**$^+$) and regenerate the *N*-ethoxyl-4-phenylpyridinyl radical, thereby leading to chain reaction. The reduction of **2** by the ethoxyl radical was shown experimentally to be exergonic and computationally to have a low reaction

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barrier, providing support for this novel reaction step. Global fitting of the chain kinetics for the reaction of *N*-alkoxylpyridinium cations with **2** provided a rough estimate for the rate constant for HAT from the ethoxyl radical to **2** of $\sim 5 \times 10^{7}$ M^{-1} s^{-1}.

While hydrogen atom transfer from alkoxyl radicals and to pyridine derivatives rationalized the previously reported photoreductive cleavage of *N*-alkoxylpyridinium cations,[10] no direct experimental evidence for the key HAT step was obtained. We describe herein experiments to directly investigate this novel reaction.

■ RESULTS AND DISCUSSION

To directly study the proposed reaction of alkoxyl radicals with pyridines described above it was desirable to isolate the hypothetical hydrogen atom transfer (HAT) from the remainder of the chain reaction steps. Nanosecond transient absorption spectroscopy (NTAS) seemed like an appropriate technique to generate alkoxyl radicals and directly probe their rapid reactions with pyridines. For practical reasons, we chose to photochemically generate the ethoxyl radical from diethyl peroxide in the presence of pyridine bases and detect the resulting transient products by transient UV−vis spectroscopy. Diethyl peroxide is a convenient source of the ethoxyl radical, as it is stable enough to handle, does not thermally decompose on the timescale of NTAS experiments, and photochemically dissociates to give two ethoxyl radicals without generating any byproducts. In principle, ethoxyl radicals can be generated from diethyl peroxide by either direct irradiation or triplet-sensitized energy transfer.[12] The former approach proved to be more useful for the present purposes because it results in simpler kinetics, as the ethoxyl radicals are effectively formed instantly on the nanosecond timescale. As described below, our NTAS apparatus allows ethoxyl radicals to be generated by 308 nm excitation using ∼15 ns pulses with transient spectra and kinetics measured over the same spectra range (∼320 to 800 nm).

NTAS experiments were first used to demonstrate that ethoxyl radicals were readily generated from diethyl peroxide by photolysis. For this purpose, 308 nm nanosecond irradiation of diethyl peroxide in acetonitrile was conducted in the presence of 50 mM 4-phenylphenol to determine if the 4-phenylphenoxyl radical was formed by reaction with the ethoxyl radical. In practice, the characteristic transient spectrum of the 4-phenylphenoxyl radical ($\lambda_{max} \sim 350$, 500, and 560 nm)[13] was cleanly produced, demonstrating sufficient production of ethoxyl radicals for our purposes (see Figure 1). The rate constant for reaction of the ethoxyl radical with 4-phenylphenol determined from a plot of the pseudo-first-order reaction rate constant vs. [4-phenylphenol] was 1.6×10^{7} M^{-1} s^{-1} (see the inset in Figure 1), which is slightly greater than the rate constant previously measured for hydrogen atom abstraction from phenol by the cumyloxyl radical in acetonitrile (5.8×10^{6} M^{-1} s^{-1}).[14]

Having confirmed the generation of ethoxyl radicals by 308 nm photolysis of diethyl peroxide, we next turned to reaction of the radical with 2,6-lutidine (**2**), which was previously proposed in the photoreduction of the *N*-ethoxylpyridinium cations in the presence of **2**.[10] Photolysis of diethyl peroxide in acetonitrile in the presence of 0.25 M **2** produced the transient absorption spectrum shown in Figure 2 (black line), recorded 500 ns after the laser pulse. This spectrum, although not particularly characteristic, agrees with that previously reported for the *N*-hydro-2,6-lutidinyl radical ($\mathbf{2H}^{\bullet}$).[15] We next sought to independently generate $\mathbf{2H}^{\bullet}$ for a more direct comparison with the transient species generated by reaction of the ethoxyl radical with 2,6-lutidine. $\mathbf{2H}^{\bullet}$ has previously been generated by photolysis of acetone in isopropanol containing **2**, where formation of the $\mathbf{2H}^{\bullet}$ was confirmed by electron paramagnetic resonance (EPR) spectroscopy.[16] The reaction proceeds by the initial photochemical generation of the acetone triplet state, which abstracts a hydrogen atom from isopropanol to generate two acetone ketyl radicals. The ketyl radicals react with **2** to generate $\mathbf{2H}^{\bullet}$, a reaction that likely occurs by proton-coupled electron transfer. Photolysis of a 1:1 acetone/isopropanol solution containing 0.25 M **2** gave the transient spectrum shown in red in Figure 2, which is in good agreement with the spectrum from reaction of the ethoxyl radical with **2**. Despite

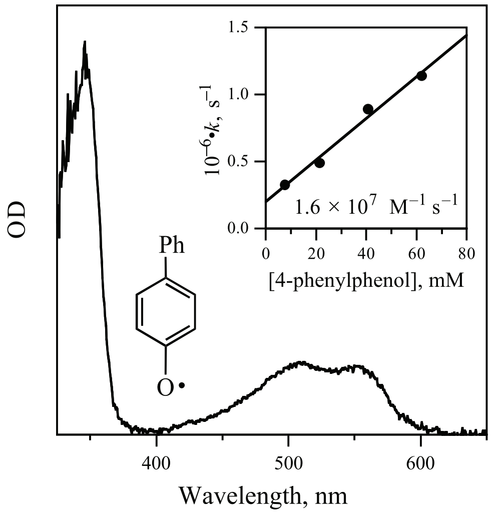


Figure 1. Transient UV−vis spectrum acquired 2 *μ*s after laser excitation from 308 nm photolysis of diethyl peroxide in argon-saturated acetonitrile with 50 mM 4-phenylphenol. The inset shows a plot of the pseudo-first-order rate constant for growth of the 4-phenylphenoxyl radical absorbance at 500 nm vs. [4-phenylphenol].

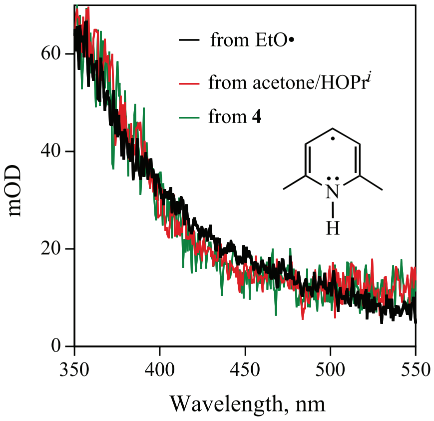
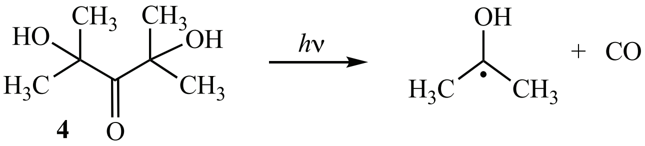


Figure 2. Transient absorption spectrum acquired after 308 nm photolysis of diethyl peroxide in the presence of 0.25 M **2** in argon-saturated acetonitrile recorded 500 ns after the laser pulse (black line). Transient absorption spectra acquired after 308 nm photoexcitation of a 1:1 acetone/isopropanol solution containing 0.25 M **2** recorded 500 ns after the laser pulse (red line). Transient absorption spectra acquired after 308 nm photoexcitation of an acetonitrile containing **4** ($OD_{308} = 1$) and 0.25 M **2** recorded 500 ns after the laser pulse (green line). Spectra are normalized for comparison.

the good agreement, this spectral comparison is not ideal due to the different solvents employed, thus we sought to generate the acetone ketyl radical in acetonitrile and measure the transient spectrum from its reaction with **2**. Fischer's ketone (**4**) was chosen as an acetone ketyl radical source (see below), as it has been shown to rapidly undergo Norrish type I cleavage under photolytic conditions to afford the acetone ketyl radical while liberating CO gas in a wide variety of solvents, including acetonitrile.[17] Photolysis (308 nm) of an acetonitrile solution of **4** (OD_{308} = 1) containing 0.25 M **2** gave the absorption spectrum shown in green in Figure 2. The good spectral agreement between the authentically generated **2H•** in acetonitrile and the transient spectrum produced from the photolysis of diethyl peroxide in the presence of **2** provides compelling evidence that the ethoxyl radical reacts with **2** to give **2H•**—a net hydrogen atom transfer reaction from an alkoxyl radical to a closed-shell molecule.



The kinetics for reaction of the ethoxyl radical with **2** were next examined. NTAS was used to measure the growth of **2H•** at 375 nm, where the cross-section of its molar absorptivity and the intensity of the analyzing light gave the best signal-to-noise ratio. Shown in Figure 3 are transient kinetic traces at various concentrations of **2**. The data show growth of **2H•** that is dependent on [**2**] followed by a slow decay that is not visible on this timescale. The growth of **2H•** is expected to be pseudo-first-order because under the conditions of the NTAS experiment [**2**] ≫ [EtO•]. The transient absorbance data were fit to first-order growth kinetics. The fitted lines in Figure 3 show the kinetic data at various values of [**2**] and are cleanly first-order at all [**2**], demonstrating the reaction is first-order in the ethoxyl radical. A plot of the growth rate constants vs. [**2**] is linear (Figure 4, square symbols), demonstrating that the growth of **2H•** is also first-order in **2**. The bimolecular rate constant obtained from the slope of this plot is 2.2 ± 0.2 × 10^7 M^{-1} s^{-1}, which is in reasonable agreement with the approximate value previously determined by global analysis of the chain kinetics for photoreduction of the *N*-ethoxylpyridinium cations in the presence of **2** (~5 × 10^7 M^{-1} s^{-1}), where multiple parameters had to be fit to estimate the rate constant for the proposed reaction of EtO• and **2**, directly demonstrated here. We note that our prior work[10] on the photochemical chain decomposition of *N*-ethoxy-4-phenylpyridinium in the presence of lutidine showed that the reaction of ethoxyl radicals with **2** cleanly produces acetaldehyde and the lutidinium cation in high yield (>95%). This rules out potential competing pathways for reaction of the ethoxyl radical with **2** (e.g., hydrogen atom abstraction or addition to the lutidine ring). Additionally, a kinetic analysis of the chain kinetics showed that the sum of rate constants for alternative competing reactions of the ethoxyl radical with **2** was ≤4 × 10^4 M^{-1} s^{-1}, i.e., >500 times less than the rate constant measured for the reaction of the ethoxyl radical with **2**.

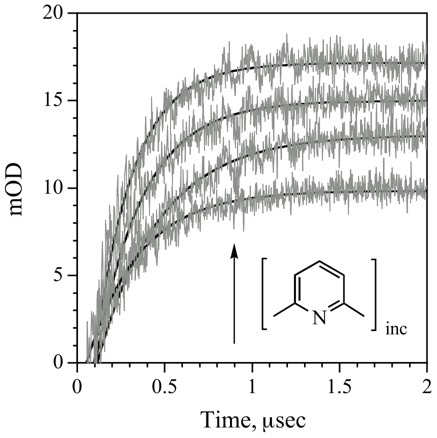


Figure 3. Kinetic traces (gray lines) acquired from the direct photolysis of diethyl peroxide in argon-saturated acetonitrile in the presence of 0.097, 0.192, 0.285, and 0.375 M **2** by monitoring the change in the optical density at 375 nm. Black lines show first-order fits.

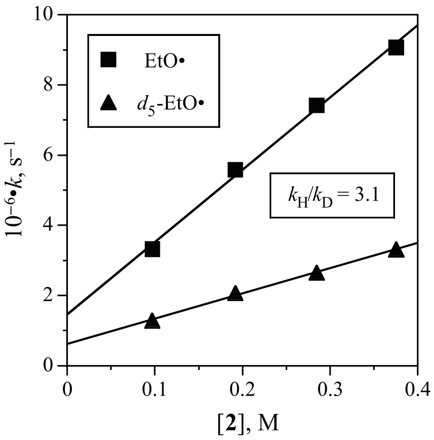


Figure 4. Plots of the pseudo-first-order rate constants (*k*) for growth of **2H•** or **2D•** from the reaction of the ethoxyl radical (square symbols) or d_5-ethoxyl radical (triangle symbols) with **2** in argon-saturated acetonitrile vs. [**2**].

As a further test of the HAT mechanism for reaction of the ethoxyl radical with **2**, the H/D kinetic isotope effect (KIE) was measured. Previous work on the photoreduction of *N*-methoxyl- vs. d_3-*N*-methoxyl-pyridinium cations in the presence of **2** were best fit with a primary KIE of ~6 for reaction of $CH_3O^•$ vs. $CD_3O^•$ with **2** to produce **2H•** or **2D•**.[10] To measure the H/D KIE for reaction of the ethoxyl radical with **2**, we chose to use perdeuterio-diethyl peroxide as the ethoxyl radical source for synthetic convenience. The deuteriums on the methyl groups of the d_5-ethoxyl radical are expected to have a negligible effect on the primary KIE for HAT. Figure 4 shows plots of the pseudo-first-order rate constants for reaction of ethoxyl (square symbols) and d_5-ethoxyl radicals (triangle symbols) with **2**. From the slopes of the best-fit lines, the H/D KIE was found to be 3.1—clearly a primary effect, consistent with a rate-determining HAT process.

We next sought to examine reaction of the ethoxyl radical with a pyridine derivative that would give a more characteristic spectrum for the corresponding *N-H*-pyridinyl radical upon HAT. 4-Phenylpyridine (**5**) was an ideal choice because the *N*-hydro-4-phenylpyridinyl radical has strong and distinct UV−vis absorption bands, enabling unambiguous assignment of its spectra. The transient spectrum from 308 nm photolysis of diethyl peroxide in acetonitrile containing 0.25 M **5** is shown in Figure 5 (black trace). A nearly identical spectrum was

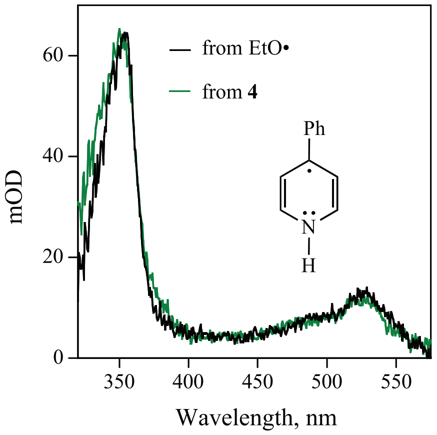
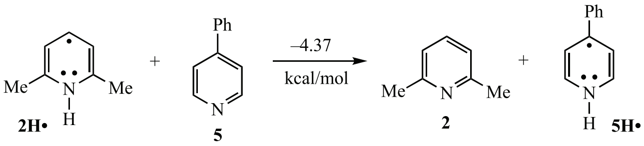


Figure 5. Transient absorption spectra acquired 500 ns after 308 nm photolysis of diethyl peroxide in argon-saturated acetonitrile (black line) or of **4** (green line) in the presence of 0.25 M **5**. Spectra are normalized for comparison.

obtained from 308 nm photolysis of an acetonitrile solution containing Fischer's ketone (**4**) and **5** (Figure 5, green trace). Both of these spectra agree well with that previously reported for the *N*-hydro-4-phenylpyridinyl radical (**5H**$^\bullet$).[18]

Typical transient kinetics traces for the reaction of the ethoxyl radical with **5** are shown in Figure 6a, monitoring the growth of **5H**$^\bullet$ at 530 nm. As with the reaction of the ethoxyl radical with **2**, the rate constant for growth of the **5H**$^\bullet$ pyridinyl radical increases with increasing [**5**]. The first-order rate constants for growth of **5H**$^\bullet$ were determined as described above. Plots of the rate constants vs. [**5**] were linear (Figure 6b). The bimolecular rate constant obtained from the slopes of plots of k vs. [**5**] for several independent kinetic measurements was found to be $6.7 \pm 0.3 \times 10^6$ M^{-1} s^{-1}. The kinetic isotope effect for reaction of the ethoxyl radical vs. d_5-ethoxyl radical with **5** was found to be 2.3 (Figure 6b).

The combined NTAS data for the reaction of the ethoxyl radical with 2,6-lutidine (**2**) and 4-phenylpyridine (**5**) provide compelling support for a novel reaction pathway where an alkoxyl radical acts as a hydrogen atom donor toward a closed-shell molecule. It is notable that the rate constant for reaction of the ethoxyl radical with **5** is ~3 times less than with **2**. If the stability of the product pyridinyl radical played a dominant role in determining the reaction rate constant, one might have expected the rate constant for reaction of the ethoxyl radical with **5** to be significantly greater than with **2**. The more energetically favorable hydrogen atom transfer from the ethoxyl radical to **5** is supported by the isodesmic reaction shown below, where the calculated electronic energies show that the hydrogen atom transfer from **2H**$^\bullet$ to **5** is favorable by ~4 kcal mol^{-1} at the M06/6-311+G** density functional level of theory.



Previous work on the reaction of alkoxyl radicals with pyridine derivatives indicated that the reactions likely proceed by a proton-coupled electron transfer (PCET) mechanism.[10] For example, quantum chemical calculations revealed that the transition states for the net hydrogen atom transfer reactions had significant degrees of proton transfer character with very little spin density from the alkoxyl radicals being transferred to the pyridine fragments until after the transition state. A PCET mechanistic pathway predicts that the activation energy may be largely determined by the proton abstracting ability of the pyridine derivative, rather than the stability of the resulting pyridinyl radical. Thus, one might reasonably expect the basicity of the pyridine to be an important factor in determining the rate constant for the hydrogen atom transfer. The pK_as of the conjugate acids of 2,6-lutidine and 4-phenylpyridine are 6.8 and 5.3, respectively.[19] On this basis, one would expect 2,6-lutidine to be more reactive toward the ethoxyl radical than 4-phenylpyridine if a PCET mechanism was operative, consistent with the experiment. Of course, steric effects can also affect the relative reactivities, which would disfavor the reaction with 2,6-lutidine. The rate constants observed experimentally suggest that, for the reactions of the ethoxyl radical with 2,6-lutidine vs. 4-phenylpyridine, electronic factors outweigh steric effects. Although attempts were made to measure rate constants for reaction of the ethoxyl radical with a number of other substituted pyridines of varying pK_a, these efforts were thwarted by low NTAS signals that did not permit confident assignment of the corresponding pyridinyl radicals. However, further support for a PCET

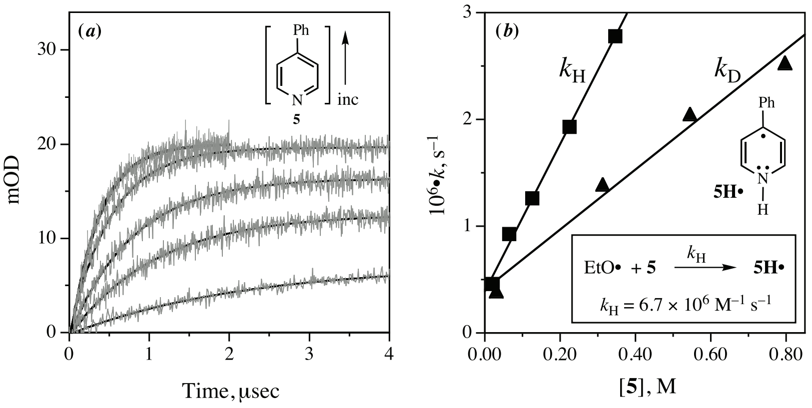


Figure 6. (a) Kinetic traces (gray) acquired from the direct photolysis of diethyl peroxide in argon-saturated acetonitrile in the presence of 0.00206, 0.0649, 0.126, 0.225, and 0.346 M **5** by monitoring the change in the optical density at 530 nm. Black lines show first-order fits. (b) Plot of the pseudo-first-order rate constants for growth of **5H**$^\bullet$ or **5D**$^\bullet$ from the reaction of the ethoxyl radical (k_H) or d_5-ethoxyl radical (k_D) with **5** in argon-saturated acetonitrile vs. [**5**].

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mechanism for the hydrogen atom transfer was provided by solvent effects on the rate constants for reaction of the ethoxyl radical with **5**, which were measured using a homologous series of nitrile solvents with dielectric constants (ε) varying from ~37 to 20. Over this solvent polarity range, the rate constants for hydrogen atom transfer show small but continuous decreases with decreasing solvent polarity (Table 1), consistent with a PCET mechanism for hydrogen atom transfer.

Table 1. Rate Constants for Reaction of the Ethoxyl Radical With 4-Phenylpyridine in Nitrile Solvents of Varying Dielectric Constant (ε)

solvent	ε	rate constant $10^{-6}\,k$ ($M^{-1}\,s^{-1}$)
acetonitrile	36.8	6.7 (2)[a]
propionitrile	28.3	5.5 (1)
butyronitrile	23.8	4.4 (1)
valeronitrile	20.2	3.9 (1)

[a] Standard deviation in the last significant digit given in parentheses.

■ CONCLUSIONS

The products and kinetics for reaction of the photochemically generated ethoxyl radical with 2,6-lutidine (**2**) and 4-phenylpyridine (**5**) were directly determined by nanosecond transient absorption spectroscopy. The ethoxyl radical was found to rapidly react with both **2** and **5** to produce the corresponding, substituted *N*-hydropyridinyl radicals. The reaction rates were found to be first-order in both the ethoxyl radical and the substituted pyridine. Both hydrogen atom transfer reactions exhibit primary H/D kinetic isotope effects. These are the first direct experimental observations of alkoxyl radical reactions with substituted pyridine bases, and the combined observations show that primary alkoxyl radicals behave as hydrogen atom donors in the presence of pyridine bases. It will be interesting to explore in future work what other basic substrates capable of accepting a hydrogen atom may react in a similar manner with alkoxyl radicals. Of note, the reaction of the benzyloxyl radical with dimethyl sulfoxide has recently been proposed to proceed by a PCET process, although no stable species resulting from net hydrogen atom transfer was observed in this case.[20] As pointed out previously,[10] there may well be examples of HAT reactions from endogenously produced alkoxyl radicals to biological bases in DNA, RNA, and proteins. Such reactions may serve to fortuitously protect organisms from the otherwise deleterious effects of reactive oxygen species (ROS). The present work shows how research along these lines may uncover important, previously unrecognized or undetected reactions of biological importance.

■ EXPERIMENTAL SECTION

Materials. Unless otherwise noted, all materials were obtained from commercial sources. Acetonitrile was passed through a column of activated alumina from a solvent purification system before use.[21] 2,6-Lutidine was distilled from $AlCl_3$ under a nitrogen atmosphere before use. 4-Phenylpyridine was recrystallized from 1:1 methanol/water, dried, and sublimed before use. 4-Phenylphenol was recrystallized from 40% aqueous ethanol and vacuum dried before use. 2,4-Dihydroxy-2,4-dimethylpentan-3-one[22] (**4**), diethyl peroxide,[23] and d_5-ethyl methanesulfonate[24] were prepared by literature procedures.

^{2}H NMR spectra were recorded at 61 MHz. ^{13}C NMR spectra were recorded at 125 MHz.

Preparation of d_{10}-Diethyl Peroxide. A two-neck 25 mL round-bottom flask equipped with a short-path distillation head, an internal thermometer, and a Teflon-coated magnetic stir bar was charged with 1.51 g (11.7 mmol) of d_5-ethyl methanesulfonate, 0.857 g (8.92 mmol) of 36 wt % aqueous hydrogen peroxide, and 0.0023 g (0.008 mmol) of stearic acid under a nitrogen atmosphere. The reaction flask was placed in an ice-water bath until the internal temperature was ~0 °C. Then, a solution of 0.954 g (15.0 mmol) of 88% potassium hydroxide in 1.1 mL of water was added over 10 min via syringe pump while maintaining the internal temperature between 0 and 5 °C. After the addition was complete, the reaction mixture was allowed to warm to room temperature and stirred for 40 min. The reaction flask was then placed in an oil bath and heated to 90 °C. Upon warming, a colorless liquid distilled out of the reaction flask and was collected in a receiving flask immersed in an ice-water bath. The colorless distillate was passed through a small amount of anhydrous Na_2SO_4 to give 0.243 g (2.43 mmol, 41%) of a colorless liquid that was pure enough for subsequent use.

^{2}H NMR (61 MHz, CH_2Cl_2/CD_2Cl_2): δ 3.96 (s, 4.0 H), 1.13 (s, 6.0 H).

$^{13}C\{^1H\}$ NMR (125 MHz, CD_2Cl_2): δ 68.6 (sept J = 21.8 Hz), 12.1 (quint, J = 27.5 Hz).

HRMS (ESI-TOF) m/z $[M]^+$ calcd for $C_4D_{10}O_2$ 100.1308; found 100.1311.

Nanosecond Transient Absorption Spectroscopy. A XeCl excimer laser (15 ns pulse width) was used for 308 nm excitation. Transient spectral absorptions were monitored at a right angle to the laser excitation by using a home-built, xenon flashlamp system equipped with a Perkin-Elmer FX-193 flashlamp to generate the analyzing light. The analyzing light was focused on the end of a fiber optic cable and then onto the entrance slit of a monochromator equipped with an intensified CCD. A pulsed xenon arc lamp was used as the monitoring light source for kinetics analyses. The monitoring light was passed through a monochromator and detected using a photomultiplier tube. The signal from the PMT was directed into a digitizing oscilloscope and then to a computer for viewing, storage, and data analysis. All transient experiments were conducted at room temperature (20 °C).

Representative Procedure for the Generation and Observation of *N*-Hydropyridinyl Radicals from Photolysis of Diethyl Peroxide. A dry 5 mL volumetric flask was charged with 0.0715 g (0.461 mmol) of 4-phenylpyridine and diluted to the mark with acetonitrile. Part of this solution (2.0 mL) was added to a dry stopcocked, quartz cuvette and gently purged for 25 min with argon that was passed through a bubbler containing a frit immersed in acetonitrile. Then, diethyl peroxide (200 μL) was added to the cuvette. The transient absorption spectrum was collected 500 ns after the 308 nm laser pulse.

Procedure for the Generation and Observation of *N*-Hydropyridinyl Radicals from Photolysis of Acetone/Isopropanol. A dry 5 mL volumetric flask was charged with 0.133 g (1.24 mmol) of 2,6-lutidine and diluted to the mark with 1:1 v/v acetone/isopropanol. The solution was transferred to a dry stopcocked, quartz cuvette and gently purged for 20 min with argon that was passed through a bubbler containing a frit immersed in 1:1 acetone/isopropanol. The cuvette was then photolyzed on the nanosecond transient absorption system at 308 nm. The transient UV−vis spectrum was recorded 500 ns after the laser pulse.

Representative Procedure for the Generation and Observation of *N*-Hydropyridinyl Radicals from Photolysis of 4. A dry 5 mL volumetric flask was charged with 0.133 g (1.24 mmol) of 2,6-lutidine, 40 μL (~0.3 mmol) of **4** and diluted to the mark with acetonitrile. The solution was then transferred to a dry stopcocked, quartz cuvette and gently purged for 20 min with argon that was passed through a bubbler containing a frit immersed in acetonitrile. The cuvette was then photolyzed on the nanosecond transient absorption system at 308 nm. The transient UV−vis spectrum was recorded 500 ns after the laser pulse.

Representative Procedure for Determining Rate Constants for the Reaction of Ethoxyl Radical With Substituted

Pyridines. A dry stopcocked cuvette containing 1 mL of a 0.9 M diethyl peroxide in acetonitrile-saturated argon was prepared. After 308 nm excitation, the optical density at 530 nm was determined vs. time following incremental additions of a solution of 4-phenylpyridine in argon-saturated acetonitrile containing 0.9 M diethyl peroxide.

Computations. All calculations were carried out with Spartan'18[25] using the M06 density functional.[26] Open-shell calculations were performed with the unrestricted UM06 method. Geometry optimizations were performed with a 6-311+G** basis set.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.joc.1c00504.

NMR spectra (^{2}H and ^{13}C); representative kinetic data (PDF); calculated geometries and energies (PDF)

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Notes

The authors declare no competing financial interest.

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