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Phenyl Bridging in Ring-Substituted Cumyloxyl Radicals. A Product and Time-Resolved Kinetic Study†

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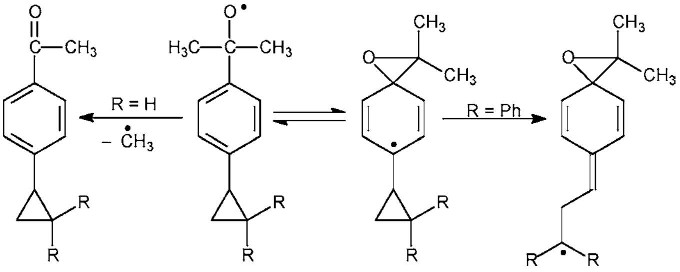
ABSTRACT

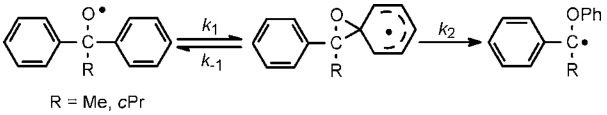


The reactivity of cumyloxyl radicals bearing cyclopropyl and 2,2-diphenylcyclopropyl groups in the para position has been investigated. Depending on radical structure, products deriving from C−C *β*-scission and/or cyclopropyl ring-opening are observed, supporting the hypothesis that cumyloxyl (and, more generally, arylcarbinyloxyl) radicals exist in equilibrium with 1-oxaspiro[2,5]octadienyl radicals, in full agreement with the previously proposed mechanism for the *O*-neophyl rearrangement of 1,1-diarylalkoxyl radicals.

The 1,2-migration of an aryl group in arylcarbinyloxyl radicals (*O*-neophyl rearrangement) has been the subject of several studies.[1−3] This process, observed for radicals bearing two or three aryl groups on the α-carbon, converts an oxygen radical into a carbon radical.

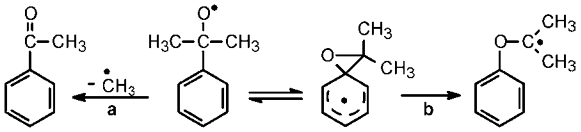
Recently, theoretical studies provided convincing support to the hypothesis that the *O*-neophyl rearrangement of 1,1-diarylalkoxyl radicals proceeds through the reversible formation of an intermediate 1-oxaspiro[2,5]octadienyl radical (Scheme 1).[4,5]

Scheme 1



According to this picture, it is reasonable to expect that the cumyloxyl radical also exists in equilibrium with a bridged radical (Scheme 2). However, no evidence in this respect is presently available. The cumyloxyl radical is known to undergo C-CH_3 β-scission as the exclusive

Scheme 2



[†] Dedicated to Keith U. Ingold on the occasion of his 80th birthday.

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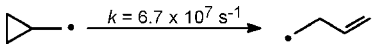
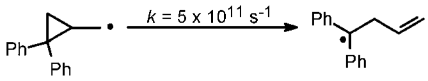
unimolecular reaction (Scheme 2, path a),[6,7] and the failure to observe the *O*-neophyl rearrangement (path b) reasonably reflects the lower stability of the 2-phenoxy-2-propyl radical as compared to the 1-phenoxy-1-phenylalkyl one displayed in Scheme 1. In this context, we felt that by introducing an appropriate *reporter group* on the aromatic ring, the bridged radical derived from ring closure in the cumyloxyl radical may undergo a sufficiently fast rearrangement able to divert it from the equilibrium shown in Scheme 2. This evidence would support the hypothesis that cumyloxyl (and, more generally, arylcarbinyloxyl) radicals exist in equilibrium with 1-oxaspiro[2,5]octadienyl radicals. A suitable candidate for this purpose appears to be a *para* cyclopropyl substituent as it is known that the cyclopropylcarbinyl radical undergoes ring-opening to the 3-butenyl radical with $k = 6.7 \times 10^7$ s^{-1} (eq 1).[8]



(1)

However, as compared to the cyclopropylcarbinyl radical, the bridged radical derived from *p*-cyclopropylcumyloxyl (if formed) would be strongly stabilized by the cyclohexadienyl system, and a significantly lower rate constant for ring-opening can be expected. The 2,2-diphenylcyclopropyl group seems a better choice, because the rate constant for the 2,2-diphenylcyclopropylcarbinyl → 1,1-diphenyl-3-butenyl radical rearrangement has been determined as $k = 5 \times 10^{11}$ s^{-1} (eq 2).[9]



(2)

In addition, the rearranged 1,1-diphenylalkenyl radical is characterized by an absorption band centered at 335 nm,[10−12] a feature that makes the study of these processes possible by time-resolved absorption spectroscopy.

Phenyl-substituted cyclopropyl groups have been extensively applied as reporter groups for the study of a variety of radical reactions,[10−14] however, to our knowledge, their application to the study of cyclohexadienyl radicals is unprecedented.

In order to obtain information on the role of phenyl bridging in arylcarbinyloxyl radicals, we have carried out product and time-resolved kinetic studies on the reactivity of the 2-(4-cyclopropylphenyl)-2-propoxyl ($\mathbf{1}^{\bullet}$), 2-(4-(2,2-diphenylcyclopropyl)phenyl)-2-propoxyl ($\mathbf{2}^{\bullet}$), and 2-(4-(2,2-diphenylcyclopropyl)phenyl)-2-butoxyl ($\mathbf{3}^{\bullet}$) radicals whose structures are shown in Figure 1.

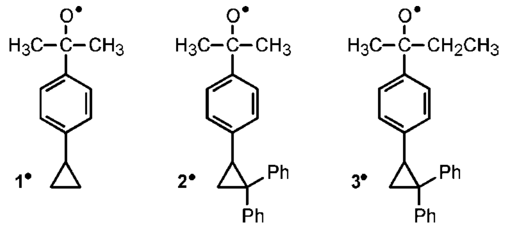
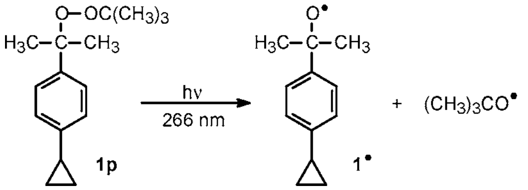


Figure 1. Structures of alkoxyl radicals $\mathbf{1}^{\bullet}$−$\mathbf{3}^{\bullet}$.

$\mathbf{1}^{\bullet}$ has been generated in MeCN by 266 nm laser flash photolysis (LFP) of the parent peroxide **1p** (eq 3).



(3)

Figure 2 displays the time-resolved absorption spectra observed after LFP of an Ar-saturated MeCN solution containing **1p**, showing after 160 ns (filled circles) a spectrum characterized by two bands centered at 320 and 540 nm, that, in full agreement with the spectra of ring-substituted cumyloxyl radicals,[6,15,16] is assigned to $\mathbf{1}^{\bullet}$.

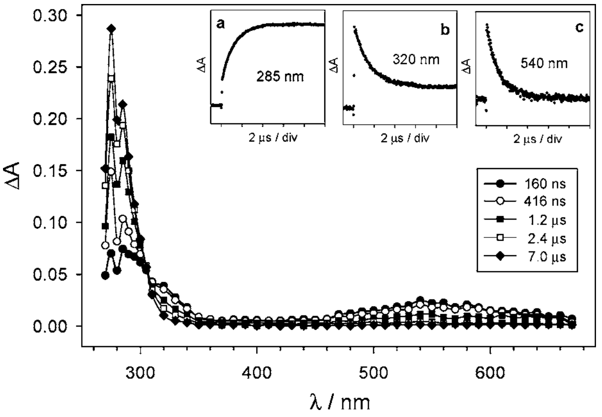


Figure 2. Time-resolved spectra observed after 266 nm LFP of **1p** (2.0 mM) in an Ar-saturated MeCN solution ($T = 25$ °C) at 160 ns (filled circles), 416 ns (empty circles), 1.2 μs (filled squares), 2.4 μs (empty squares), and 7.0 μs (diamonds), after the 8 ns, 10 mJ pulse. Insets: (a) first-order buildup at 285 nm; (b) first-order decay at 320 nm; (c) first-order decay at 540 nm.

The observation of a band centered at 540 nm is in full agreement with the electron-donating character of the cy-

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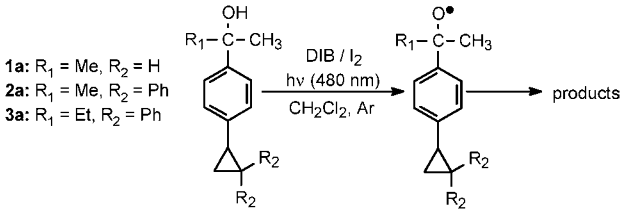
clopropyl substituent, as it is known that the position of the cumyloxyl radical visible absorption band, centered at 485 nm, is red-shifted by electron releasing ring-substituents.[6,15,16] **1**$^\bullet$ undergoes a first-order decay (insets **b** and **c**: $k_{\downarrow} = 8.0 \times 10^5\ \mathrm{s}^{-1}$) accompanied by a corresponding buildup at 285 nm (inset **a**: $k_{\uparrow} = 8.0 \times 10^5\ \mathrm{s}^{-1}$) that, in line with previous studies on cumyloxyl radicals,[6,17,18] is assigned to 4-cyclopropylacetophenone (**4**) (an isosbestic point is visible at 305 nm), formed after C−CH_3 β-scission in **1**$^\bullet$. Quite importantly, the rate constant measured for β-scission of **1**$^\bullet$ (k_β) is in line with those measured previously in MeCN for a series of ring-substituted cumyloxyl radicals ($k_\beta = 0.7-1.0 \times 10^6\ \mathrm{s}^{-1}$),[6] confirming that β-scission is not significantly influenced by ring substitution. As expected, the 540, 320, and 285 nm bands were not affected by the presence of oxygen.

With peroxides **2p** and **3p**, a very strong emission was observed in the region below 400 nm following 266 nm LFP (see Figures S2 and S3, Supporting Information) and no evidence for the formation of radicals **2**$^\bullet$ and **3**$^\bullet$ was obtained. An analogous behavior was observed after 266 nm LFP of the corresponding arylalkanols **2a** and **3a** (see Figure S4, Supporting Information). With all these systems, the presence of the diphenylcyclopropyl group leads to a strong emission in the region below 400 nm. Unfortunately, the emission observed with **2p** and **3p** does not allow clear evidence for the formation of a species absorbing at 335 nm, indicative of a 2,2-diphenylcyclopropylcarbinyl → 1,1-diphenyl-3-butenyl type radical rearrangement, to be obtained (see the Supporting Information).

Product Studies. Arylcarbinyloxyl radicals **1**$^\bullet$−**3**$^\bullet$ have been generated photochemically by visible light irradiation of CH_2Cl_2 solutions containing the parent arylalkanols (**1a**−**3a**), (diacetoxy)iodobenzene (DIB), and I_2. It is well established that under these conditions the DIB/I_2 reagent converts alcohols into hypoiodites that are then photolyzed to give alkoxyl radicals, precursors of the observed reaction products (Scheme 3).[2,19,20]

Scheme 3

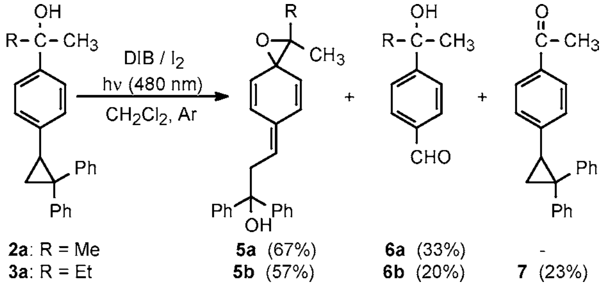


Under these conditions, reaction of **1a** led to the exclusive formation of 4-cyclopropylacetophenone (**4**).

Reaction of **2a** led to the formation of 2,2-dimethyl-6-(3-hydroxy-3,3-diphenylpropyliden)-1-oxaspiro[2,5]octa-4,7-diene (**5a**) and 4-(2-hydroxy-2-propyl)benzencarbaldehyde (**6a**) in 67% and 33% yield, respectively (Scheme 4).

Reaction of **3a** led to the formation of 2-ethyl-2-methyl-6-(3-hydroxy-3,3-diphenylpropyliden)-1-oxaspiro[2,5]octa-4,7-diene (**5b**), 4-(2-hydroxy-2-butyl)benzencarbaldehyde (**6b**), and 4-(2,2-diphenylcyclopropyl)acetophenone (**7**) in 57%, 20%, and 23% yield, respectively (Scheme 4).

Scheme 4



Products **5a** and **5b** have been isolated and unambiguously characterized by ^{1}H NMR, ^{13}C NMR, and correlation NMR (see the Supporting Information). Aldehydes **6a** and **6b** have been identified by comparison with authentic samples (see the Supporting Information). It is, however, important to point out that when the reaction mixtures obtained after irradiation of substrates **2a** and **3a** in the presence of DIB and I_2 were analyzed by ^{1}H NMR *prior* to workup, no trace of aldehydes **6a** and **6b** was detected, clearly indicating that these products are formed during workup and are not primary products deriving from the reactions of the intermediate alkoxyl radicals **2**$^\bullet$ and **3**$^\bullet$.[21]

The results obtained in the product and time-resolved studies can be rationalized on the basis of the mechanisms shown in Scheme 5. Irradiation of **1a** led to the formation of 4-cyclopropylacetophenone (**4**), indicating that under these conditions the intermediate cumyloxyl radical **1**$^\bullet$ undergoes exclusive β-scission (Scheme 5, path a, R = H), in full agreement with the results of the LFP experiments described above. Of course, in this case, no information on the existence of an equilibrium between **1**$^\bullet$ and the bridged cyclopropylcarbinyl radical (path b) could be obtained. If formed, the latter radical would strongly benefit from the stabilization imposed by the cyclohexadienyl system, and accordingly, in **1**$^\bullet$ cyclopropyl ring-opening (path c) is not expected to compete to any significant extent with β-scission.

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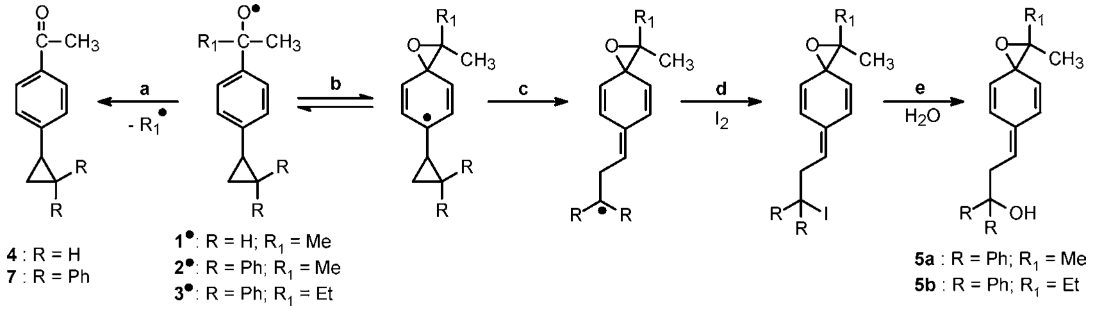
(21) The ^{1}H NMR spectrum obtained after irradiation of **3a** in the presence of DIB and I_2 in CD_2Cl_2, registered prior to workup (see the Supporting Information), showed the formation of **5b** and **7** in 76% and 24% yield, respectively. The observation that the amount of **5b** obtained in this experiment is equal, within experimental error, to the sum of **5b** and **6b** obtained after workup (77%, see Scheme 4) clearly indicates that **6b** derives from the decomposition of the first formed **5b**.

Scheme 5



With **2a**, irradiation led to the exclusive formation of **5a**.[22] The formation of this product can be rationalized in terms of cyclopropyl ring opening in the intermediate bridged radical (Scheme 5, pathways c−e, R = Ph; R_1 = Me),[23] supporting the hypothesis that this radical exists in equilibrium with **2**$^\bullet$. The failure to observe **7**, deriving from β-scission in **2**$^\bullet$, clearly indicates that in the presence of two phenyl substituents on the cyclopropyl group, ring-opening occurs significantly faster than C−Me β-scission. By considering that in ring-substituted cumyloxyl radicals k_β is not significantly influenced by the nature of the substituent,[6] it is reasonable to assume the same rate constant for β-scission in **2**$^\bullet$ and **1**$^\bullet$ ($k_\beta = 8.0 \times 10^5$ s^{-1}). Along this line, and considering the results of product studies described above, it is possible to place a lower limit to the rate constant for cyclopropyl ring-opening in the bridged radical in equilibrium with **2**$^\bullet$ as $k \geq 10^8$ s^{-1}.

With **3a**, irradiation led to the formation of **5b** and **7**, in a 3:1 ratio.[21] Compound **5b** derives from cyclopropyl ring-opening in the intermediate bridged radical (Scheme 5, pathways c−e, R = Ph; R_1 = Et), whereas **7** is formed following C-Et fragmentation in **3**$^\bullet$ (path a, R = Ph).

By assuming, in analogy with the discussion outlined above for **2**$^\bullet$, that C−Et β-scission in **3**$^\bullet$ occurs with the same rate constant as that measured previously for C−Et β-scission in the 2-(4-methylphenyl)-2-butoxyl radical ($k_\beta = 2.5 \times 10^8$ s^{-1}),[25] and taking into account the product distribution observed for **3**$^\bullet$, a rate constant $k \approx 7.5 \times 10^8$ s^{-1} can be estimated for cyclopropyl ring-opening in the bridged radical in equilibrium with **3**$^\bullet$.

In conclusion, by means of detailed product and time-resolved studies, convincing experimental evidence in support of the existence of an equilibrium between cumyloxyl and 1-oxaspiro[2,5]octadienyl radicals has been provided. A consequence of this observation is the reopening of the debate on the nature of the visible absorption band of arylcarbinyloxyl radicals.[5,6,15−17,26,27] Given the existence of this equilibrium, and taking into account that the spiro[2,5]octadienyl radical (and, more generally, cyclohexadienyl radicals) is characterized by a broad absorption band in the visible region,[28] it is not possible to exclude that the UV and visible absorptions previously assigned to arylcarbinyloxyl radicals effectively arise from two species in rapid equilibrium.[15,27] Further work in our laboratory will probe this issue.

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Supporting Information Available: Details on product studies, synthesis, and characterization of arylalkanols **1a**−**3a**, peroxides **1p**−**3p**, and products **4**−**7**. This material is available free of charge via the Internet at http://pubs.acs.org.

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[22] Considering that, as mentioned above, aldehyde (**6a**) derives from the decomposition of **5a** during workup.

[23] When the DIB/I_2 system is used, carbon radicals rapidly react with I_2 to give the corresponding alkyl iodides (see refs 20 and 24); it is thus reasonable to propose that **5a** is formed during workup following solvolysis of the tertiary iodide (Scheme 5, path **e**, R = Ph; R_1 = Me).

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