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The first crystal structure of a monomeric phenoxyl radical: 2,4,6-tri-*tert*-butylphenoxyl radical†

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Crystals of the 2,4,6-tri-*tert*-butylphenoxyl radical have been isolated and characterized by X-ray diffraction, and calculations have been performed that give the distribution of spin density in the radical.

The 2,4,6-tri-*tert*-butylphenoxyl radical (**^{t}Bu$_3$ArO$^\bullet$**) has been investigated extensively for over 40 years.[1,2] This is, in part, because it is the simplest of the stable phenoxyl radicals. Both it and related radicals have served as models for aryloxyl radicals in biological systems, derived, for instance, from vitamin E (tocopherols) or tyrosine residues in proteins.[3–6] Biological systems have also stimulated interest in the coordination chemistry of phenoxyl radicals.[7] Given the stability of phenoxyl radicals, 2,4,6-tri-*tert*-butylphenol (**^{t}Bu$_3$ArOH**) and related phenols are important antioxidants.[8] For example, 2,6-di-*tert*-butyl-4-methylphenol (commonly known as BHT) is widely used as a food preservative. Despite many studies, the synthesis and characterization of phenoxyl radicals remains incomplete,[9] and the radicals are often generated from their parent phenols *in situ*. No X-ray crystal structure of a monomeric phenoxyl radical has been reported to date.[7] The closest example is an imprecise 1969 structure of galvinoxyl, an air-stable radical with one unpaired electron delocalized over two aryloxyl rings.[10] We report here an X-ray crystal structure of the monomeric phenoxyl radical **^{t}Bu$_3$ArO$^\bullet$**, together with UV-vis spectroscopy, an improved purification method and DFT calculations. The structure is a valuable benchmark for computational studies and discussions of bonding and spin density distributions in aryloxyl radicals, which have been the subject of numerous EPR measurements and calculations.[9,11,12]

Our laboratory and others have found **^{t}Bu$_3$ArO$^\bullet$** to be a very convenient reagent for hydrogen atom transfer (HAT) studies.[13] Among stable organic radicals, it is readily generated, has a high kinetic reactivity toward HAT[14,15] and has a relatively high thermodynamic affinity for H$^\bullet$: the bond dissociation enthalpy of **^{t}Bu$_3$ArOH** is 80.1 kcal mol^{-1} in benzene.[16] With a need for high purity solid samples of **^{t}Bu$_3$ArO$^\bullet$**, we modified a literature procedure[17] as follows.† Potassium ferricyanide was reacted with **^{t}Bu$_3$ArOH** in a deoxygenated biphasic mixture of benzene and 1 M NaOH in water. The solvent was removed, and the product was extracted with diethyl ether and dried *in vacuo*. The resulting powder was redissolved in dry acetonitrile, where dark blue crystals formed in the dark at −30 °C (56% yield). The identity of these crystals was confirmed by elemental analysis and UV-vis spectroscopy, where the extinction coefficient (ε at 626 nm) of 400 ± 10 M^{-1} cm^{-1} in acetonitrile is very similar to the literature value in benzene.[15,17]

^{t}Bu$_3$ArO$^\bullet$ crystallizes in the monoclinic space group *C*2/*c*. The radical lies about a two-fold axis and the *para tert*-butyl group is disordered (Fig. 1).§ The data (R_{int} of 7.80%) were refined to R_1 = 5.69% using a model in which the 4-*tert*-butyl group is disordered over two equally occupied positions. As a comparison, we have also obtained a crystal structure of the parent phenol, **^{t}Bu$_3$ArOH**, since no structure has been reported to date. Crystals were grown by slow evaporation of an acetonitrile solution. The structure,¶ however, has a three-fold disorder; the aromatic ring and the three ^{t}Bu groups are clear, but the hydroxyl group has one-third occupancy at the three positions on the ring in-between the ^{t}Bu groups. As a result, the aryl C–C bond lengths could only be solved as an averaged value. Therefore, the metrical comparison in Table 1 below also includes the reported structures of BHT[18] and 2,6-di-*tert*-butyl-4-phenylphenol (DBPP).[19]

The C1–O1 bond length in **^{t}Bu$_3$ArO$^\bullet$** is 1.246(2) Å, shorter by 0.136(4) Å than the C–O bond lengths in BHT and DBPP. The

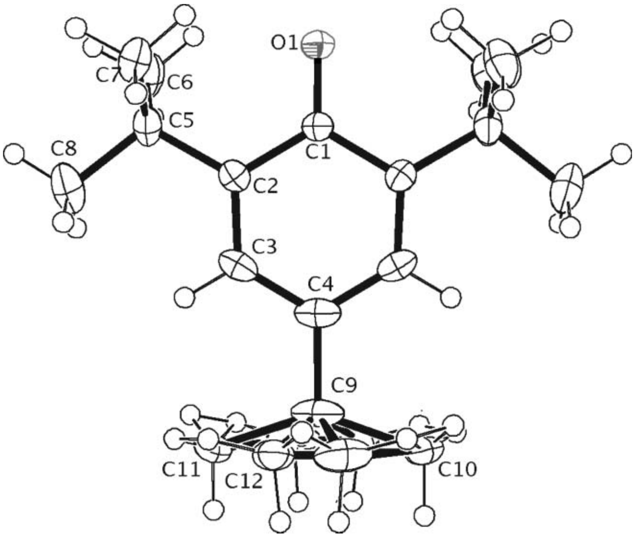

Fig. 1 ORTEP representation of **^{t}Bu$_3$ArO$^\bullet$**, with ellipsoids at 50% probability. Atoms O1, C1, C4 and C9 lie on the two-fold axis, and there is disorder of the *para*-*tert*-butyl methyl carbons bonded to C9.

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Table 1 Comparison of bond lengths (Å) from crystal structures of phenoxyl radicals and related phenols

	Phenoxyl radicals		4-R-2,6-^{t}Bu$_2$ArOH		
	${}^t\mathrm{Bu_3ArO}^{\bullet}$	Galv.[a]	R = ^{t}Bu[b]	R = Me[c]	R = Ph[d]
C1–O1	1.246(2)	1.27	1.373(12)[b]	1.383(3)	1.381(3)
C1–C2	1.4713(14)	1.41	1.401(7)[b]	1.404(5)	1.395(3)
C2–C3	1.3673(18)	1.35	1.401(7)[b]	1.398(4)	1.389(3)
C3–C4	1.4068(15)	1.41	1.401(7)[b]	1.385(5)	1.397(3)
C3′–C4	1.4068(15)[e]	1.42	1.401(7)[b]	1.382(5)	1.378(3)
C2′–C3′	1.3673(18)[e]	1.37	1.401(7)[b]	1.390(4)	1.394(4)
C1–C2′	1.4713(14)[e]	1.49	1.401(7)[b]	1.406(5)	1.413(3)

[a] Galvinoxyl radical, from ref. 10; estimated errors are ± 0.02 Å. [b] The structure of 2,4,6-^{t}Bu$_3$ArOH is three-fold disordered, making the aromatic C–C bond lengths equivalent. [c] From ref. 18. [d] From ref. 19. [e] By symmetry, C1–C2 = C1–C2′, C2–C3 = C2′–C3′ and C3–C4 = C3′–C4.

C–O bond length of 1.27 ± 0.02 Å in the galvinoxyl radical[10] is slightly longer than it is in **${}^t\mathrm{Bu_3ArO}^{\bullet}$**, although the two values are essentially within error. The C–O distance in **${}^t\mathrm{Bu_3ArO}^{\bullet}$** is almost as short as the ketone C=O bond in cyclohexanone (1.213(2) Å)[20] and, surprisingly, is exactly the same length as the C1=O bond in 2,6-di-*tert*-butyl-1,4-benzoquinone (1.246(10) Å).[21,22] The C–C bond lengths around the aromatic ring in **${}^t\mathrm{Bu_3ArO}^{\bullet}$** show substantial alternations (Fig. 2). The length of the C1–C2 bond flanking the C–O bond is 1.4713(14) Å, 0.104(2) Å longer than the C2–C3 bond length of 1.3673(18) Å. The C1–C2 bond length (1.501(2) Å) is only 0.030(2) Å shorter than the analogous saturated C1–C2 distance in cyclohexanone.[20] The C3–C4 distance of 1.4068(15) Å in **${}^t\mathrm{Bu_3ArO}^{\bullet}$** is intermediate between the C1–C2 and C2–C3 distances, and within error of the average C–C distance in **^{t}Bu$_3$ArOH** (1.401(7) Å). A similar but much less pronounced alternation of C–C bond distances is seen in BHT and DBPP, with slightly longer distances to the carbon bearing the oxygen.

These bond distances indicate that **${}^t\mathrm{Bu_3ArO}^{\bullet}$** is well-described by the standard resonance forms in Scheme 1.[2] The short ketonic C–O and long C1–C2 distances indicate that forms **II** and **III** predominate. The shorter C2–C3 *vs.* C3–C4 distances further suggest that **III** is the largest contributor. These bond lengths compare well with recent calculations of the phenoxyl[5] and α-tocopheroxyl[9] radicals, where "quinoid"-type geometries, similar to **III**, have been noted.

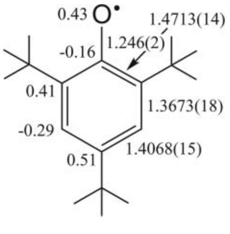
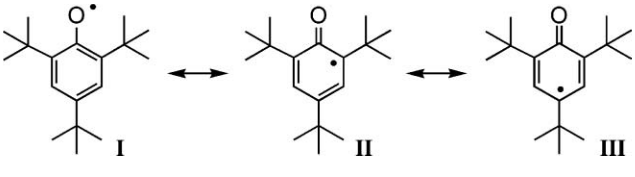


Fig. 2 Drawing of **${}^t\mathrm{Bu_3ArO}^{\bullet}$** with crystallographic bond lengths (right-hand side) and UBH&HLYP-calculated spin densities (left-hand side).



Scheme 1 Resonance structures of **${}^t\mathrm{Bu_3ArO}^{\bullet}$**.

With an experimental structure in hand, we have explored the accuracy of various hybrid DFT functionals. The geometry of **${}^t\mathrm{Bu_3ArO}^{\bullet}$** was optimized using UB3LYP, UBH&HLYP and UMPW1K[23] functionals with the 6-31G* basis set.†[24] Larger basis sets have been found to produce no improvement in geometry for phenoxyl radicals.[25] The calculated structures all have C_s symmetry, with the ring as the mirror plane. Of these methods, the UBH&HLYP structure is closest to the experimental crystallographic one, with a mean unsigned error (MUE) of 0.006 Å in the key bond lengths (Table 2). This geometry is slightly better than that of UB3LYP geometry (MUE = 0.008 Å) and is significantly better than the UMPW1K geometry (MUE = 0.015 Å). However, the $\langle S^2 \rangle$ value at UBH&HLYP (0.848) is somewhat larger than the theoretical value of 0.75, indicating some spin contamination.[26] This method slightly underestimates the bond length alternation in the ring, but the calculated $d_{\text{C–O}}$ = 1.244 Å is within the error of the experimental value (1.246(2) Å).

Using the UBH&HLYP method, a calculated spin density of 0.43 resides on the oxygen, which is only 23% of the total unpaired (α) spin density. The bulk of the remainder is on the *para*-carbon (C4, 0.51), which has 27% of the total, and the *ortho*-carbon (C2, 0.41 average), which has 22% of the total, as shown in Fig. 2. The computed spin density at the *para*-carbon is lower than the value of 32% determined from EPR spectra recorded in CCl$_4$.[11] Negative (β) spin densities are seen at the *ipso*- (C1, −0.16) and *meta*-carbon (C3, −0.29 average) positions, consistent with previous calculations on phenoxyl radicals.[9] The calculated spin density distribution and bond lengths serve as further confirmation of the canonical resonance structures of phenoxyl radicals (Scheme 1), although the predominance of structure **III** is less evident in these data.

In conclusion, the first crystal structure of a monomeric phenoxyl radical, **${}^t\mathrm{Bu_3ArO}^{\bullet}$**, is described. It is prepared by an improved procedure that yields high purity samples. The metrical data of the structure support the resonance forms typically drawn for phenoxyl radicals, and suggests that the cyclohexa-2,5-dien-1-one-4-yl structure (**III**) is the largest contributor. DFT calculations using the UBH&HLYP functional gave the best agreement with the solid state structure.[28]

Table 2 Comparison of crystallographic and calculated bond lengths (Å) for **${}^t\mathrm{Bu_3ArO}^{\bullet}$**

	${}^t\mathrm{Bu_3ArO}^{\bullet}$	BH&HLYP/6-31G*
C1–O1	1.246(2)	1.244
C1–C2	1.4713(14)	1.460
C2–C3	1.3673(18)	1.376
C3–C4	1.4068(15)	1.401
C3′–C4	1.4068(15)[a]	1.409
C2′–C3′	1.3673(18)[a]	1.369
C1–C2′	1.4713(14)[a]	1.463
Bond alternation[b]	0.0374	0.0325

[a] By crystallographic symmetry, C1–C2 = C1–C2′, C2–C3 = C2′–C3′ and C3–C4 = C3′–C4; the calculated structure has C_s symmetry. [b] The mean deviation from the average C–C bond length.

Notes and references

§ Crystals of **^{t}Bu$_3$ArO$^•$** have a disordered *tert*-butyl group in the *para* position. Refinement gives an elongated thermal ellipsoid for the quaternary carbon, suggesting that the 4-*tert*-butyl group can adopt multiple positions in the plane of the molecule. This gives rise to an anomalously long C9–C11 bond.

Crystal data for **^{t}Bu$_3$ArO$^•$**: $C_{18}H_{29}O$, M = 261.43, monoclinic, space group $C2/c$, a = 15.6814(7), b = 9.5268(5), c = 11.3995(5) Å, β = 94.948(3)°, V = 1696.58(14) Å^3, T = 130(2) K, Z = 4, D_c = 1.023 Mg m^{-3}, μ = 0.061 mm^{-1}, $F(000)$ = 580, λ = 0.71073 Å, 3093 reflections collected (R_{int} = 0.0780), 2037 unique reflections, $R1$ [$I > 2\sigma(I)$] = 0.0569, w$R2$ [$I > 2\sigma(I)$] = 0.1471, $R1$ [all data] = 0.0899, w$R2$ [all data] = 0.1675, GOF = 0.985, completeness = 99.3%. The structure was solved and refined using SHELXS-97 and SHELXL-97.[27] All non-hydrogen atoms were refined anisotropically. CCDC 658150. For crystallographic data in CIF or other electronic format see DOI: 10.1039/b712872j

¶ The structure of **^{t}Bu$_3$ArOH** was solved in the monoclinic space group $C2/c$; attempts at a solution in higher symmetry space groups, including the three-fold disorder axis, were not successful. The structure was solved with one-third of a hydroxyl group at three positions without two-thirds of a hydrogen atom, so the crystallographic formula is different to that of the actual molecular formula.

Crystal data for **^{t}Bu$_3$ArOH**: $C_{18}H_{30}O$, M = 262.44, monoclinic, space group $C2/c$, a = 10.0648(5), b = 17.4311(9), c = 19.6355(9) Å, β = 90.185(3)°, V = 3444.8 Å^3, T = 130(2) K, Z = 8, D_c = 1.003 Mg m^{-3}, μ = 0.060 mm^{-1}, $F(000)$ = 1151, λ = 0.71073 Å, 6571 reflections collected (R_{int} = 0.0623), 3479 unique reflections, $R1$ [$I > 2\sigma(I)$] = 0.0643, w$R2$ [$I > 2\sigma(I)$] = 0.1479, $R1$ [all data] = 0.1640, w$R2$ [all data] = 0.1983, GOF = 0.944, completeness = 98.8%. The structure was solved and refined using SHELXS-97 and SHELXL-97.[27] All non-hydrogen atoms were refined anisotropically. CCDC 658151. For crystallographic data in CIF or other electronic format see DOI: 10.1039/b712872j

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