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A Carbon-Centered Radical Unreactive Toward Oxygen: Unusual Radical Stabilization by a Lactone Ring

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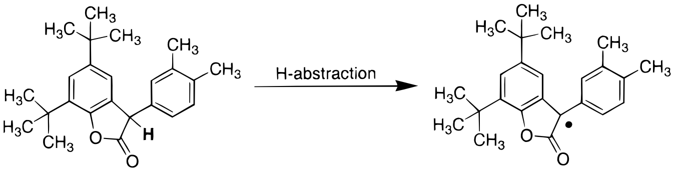
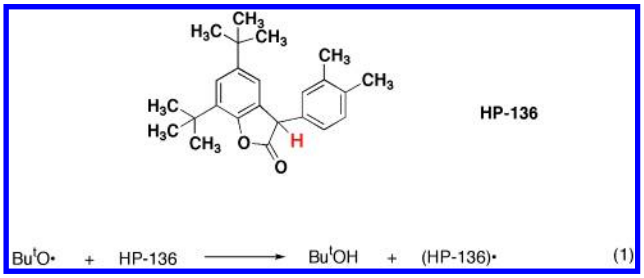
ABSTRACT



A lactone ring confers unusual stability to a diphenylmethyl-like radical that is virtually unreactive toward oxygen. Thus, the radical derived from HP-136 is about 10 000 times less reactive than typical carbon-centered radicals. A reversible reaction with oxygen is proposed by analogy with triphenylmethyl; however, the association constant is about 1000 times smaller for HP-136 than for triphenylmethyl. While the lactone ring greatly influences the reactivity, the spectroscopy of the HP-136-derived radical is in line with that expected for a substituted diphenylmethyl radical.

Antioxidants rarely involve the cleavage of C−H bonds. This is due to the fact that the vast majority of carbon-centered radicals react with dioxygen readily,[1] leading to peroxyl radicals that then propagate the oxidative chain. Thus, it is not sufficient for a molecule to be a good hydrogen donor for it to be an antioxidant. In addition, the radical produced must be unable to propagate the autoxidation chain. Some antioxidants, notably phenols, can produce radicals that not only do not propagate the autoxidation chain but can themselves trap a second radical, thus leading to a 2-to-1 stoichiometry for the radical-mediated antioxidant steps.[2]

We were surprised by CIBA's recent claims that HP-136 was an excellent antioxidant for high-temperature polymer processing. Examination of the structure of HP-136 reveals the benzylic C−H bond as the only anticipated good hydrogen donor site. Abstraction, as illustrated in reaction 1, by *tert*-butoxyl radicals should lead to a carbon-centered radical,[3] virtually identical to the diphenylmethyl radical. Indeed, photolysis of di-*tert*-butyl peroxide in the presence



$$\mathrm{Bu^tO\bullet} + \text{HP-136} \longrightarrow \mathrm{Bu^tOH} + (\text{HP-136})\bullet \qquad (1)$$

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(1) Maillard, B.; Ingold, K. U.; Scaiano, J. C. *J. Am. Chem. Soc.* **1983**, *105*, 5095.

(2) Ingold, K. U. *Acc. Chem. Res.* **1969**, *2*, 1.

(3) Paul, H.; Small, R. D., Jr.; Scaiano, J. C. *J. Am. Chem. Soc.* **1978**, *100*, 4520.

(4) Chatgilialoglu, C. In *Handbook of Organic Photochemistry*; Scaiano, J. C., Ed.; CRC Press: Boca Raton, FL, 1989; Vol. II, p 3.

(5) Bensasson, R.; Land, E. J. *Trans. Faraday Soc.* **1971**, *67*, 1904.

(6) Land, E. J. *Proc. R. Soc. London A* **1968**, *305*, 457.

(7) Avila, D. V.; Lusztyk, J.; Ingold, K. U. *J. Am. Chem. Soc.* **1992**, *114*, 6576.

(8) Howard, J. A.; Ingold, K. U. *Can. J. Chem.* **1968**, *46*, 2655.

(9) Avers, C. L.; Janzen, E. G.; Johnston, F. J. *J. Am. Chem. Soc.* **1966**, *88*, 2610.

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of HP-136 reveals the formation of the radical of Figure 1, where the UV band is virtually identical to that for diphenylmethyl.[4] The visible band (see 500−600 nm region) is more intense than that in the case of $Ph_2C^{\bullet}H$, but enhancement of this band is common when heteroatoms are involved; the best documented example is $Ph_2C^{\bullet}OH$, the ketyl radical from benzophenone.[4−6] Photolysis of dicumyl peroxide in the presence of HP-136 shows that the formation of the HP-136 radical (the same as in Figure 1) occurs concurrently with the decay of cumyloxyl. We note that cumyloxyl radicals are far more easily detectable than *tert*-butoxyl and allow the easy corroboration of the precursor-derivative relationship between cumyloxyl and the HP-136 radical.[7]

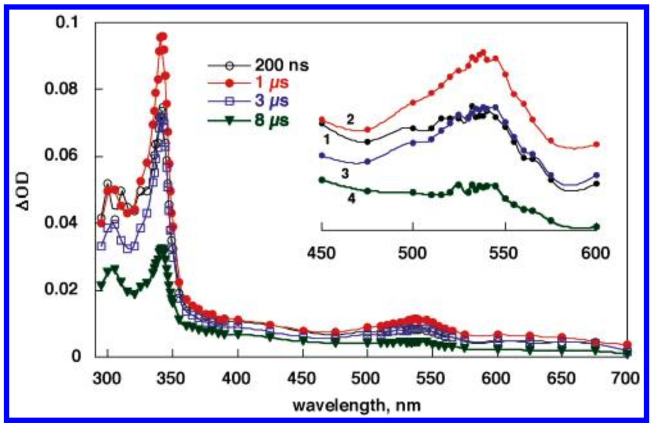


Figure 1. Transient spectra recorded following 308 nm laser excitation of a sample containing 1% (w/v) HP-136 and 5% (v/v) di-*tert*-butyl peroxide in acetonitrile under nitrogen. Monitored at different times following the laser pulse, where the signal grows and decays as indicated. The inset shows an expansion of the visible region and facilitates visualizing the order of the traces.

In an experiment, $Ph_2C^{\bullet}H$ was produced by laser irradiation of di-*tert*-butyl peroxide in the presence of diphenylmethane. When the sample was saturated with oxygen, the signal from $Ph_2C^{\bullet}H$ was totally quenched, with barely a fast spike indicating its presence in the early stages following the laser pulse. Remarkably, when the same experiment was repeated with HP-136, oxygen did not cause any appreciable changes in the rate of decay of the radical. Taking this lack of quenching to reflect radical unreactivity toward oxygen would lead to an upper limit for its reacton with oxygen of $\leq 10^5$ M^{-1} s^{-1}, i.e., over 10 000 times less reactive than typical free radicals.[1] Careful comparison of nitrogen- and oxygen-saturated samples, at either the 340 or 540 nm maxima, shows that while neither the decay nor the growth kinetics are significantly affected by oxygen (see Figure 2), the signal amplitude was 18% smaller in the presence of oxygen. The true decrease is smaller than suggested by this figure; it can be attributed to two origins, which we label trivial and nontrivial. A trivial decrease of 11% is due to an enhancement of the solution absorption at 308 nm (laser excitation wavelength) in the presence of oxygen. Such charge-transfer-mediated enhancements are common, although they are frequently overlooked or believed to be significantly smaller. The remaining 7% decrease in signal intensity (thus contributing to the observed 18% decrease) must have a different origin. We propose that this “nontrivial” decrease should be attributed to a reversible reaction of the HP-136 radical with oxygen, as illustrated in reaction 2. This type of reversibility is unprecedented for a diphenylmethyl-type structure but is documented for triphenylmethyl radicals, which are known to react with oxygen reversibly;[8−10] however, in this case the equilibrium is extensively displaced toward the peroxyl radical side. Howard and Ingold[8] studied this equilibrium as early as 1968 and determined an equilibrium constant of 8 × 10^3 M^{-1}, or more conveniently expressed in terms of oxygen pressure above the solution, $K = 60$ atm^{-1} at 30 °C in hydrocarbon solvents. A similar analysis for HP-136 would suggest an equilibrium constant

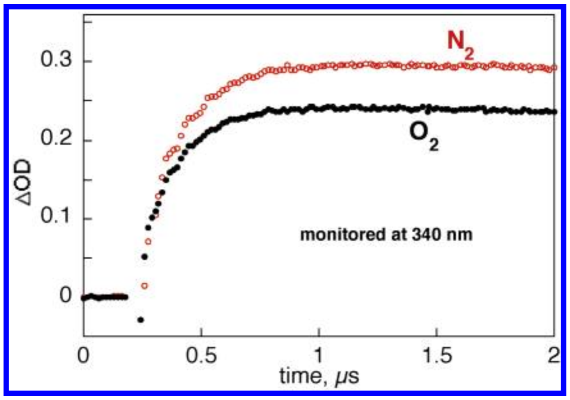
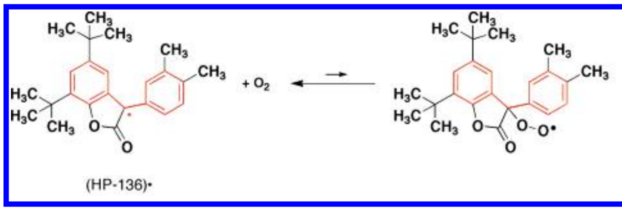


Figure 2. Transient kinetic traces recorded at 340 nm following 308 nm laser excitation of a sample containing 2.5% (w/v) HP-136 and 5% (v/v) di-*tert*-butyl peroxide in benzene under nitrogen and oxygen.



(2)

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(10) Janzen, E. G.; Johnston, F. J.; Avers, C. L. *J. Am. Chem. Soc.* **1967**, *89*, 1176.

(11) Data were collected on a Bruker AX SMART 1K CCD diffractometer, Mo Kα ($\lambda = 0.71073$ Å), in the range $4.8° \leq 2\theta \leq 45°$ using 0.3° ω scans at 0, 90, and 180° in ϕ. No absorption corrections were required ($\mu = 0.71$ cm^{-1}). Systematic absences in the diffraction data [15943 collected, 2654 observed, unique ($I > 2\sigma I$)] and unit-cell parameters [$a = 13.791(3)$ Å, $b = 10.797(2)$ Å, $c = 14.412(3)$ Å, $\beta = 108.174(3)°$, $V = 2038.9(6)$, $Z = 4$] were uniquely consistent with monoclinic, $P2_1/c$ (No. 14). A *tert*-butyl group was found rotationally disordered in two positions with a refined site occupancy distribution of 70/30. All non-hydrogen atoms were refined with anisotropic displacement parameters. All hydrogen atoms were treated as idealized contributions. $R_F(wR_F{}^2) = 0.0492$ (0.1287), GOF = 1.040. All scattering factors and anomalous dispersion factors are contained in the SHEXTL 5.10 program library (Sheldrick, G. M. Bruker AXS, Madison, WI, 1997).

for reaction 2 of ca. 0.08 atm^{-1}. This means that even accepting the hypothesis of reversibility, *the HP-136 radical is about 1000 times less reactive than triphenylmethyl toward oxygen*. While this is consistent with the manufacturer's claims, it also suggests an unprecedented lack of reactivity toward oxygen for a relatively simple carbon-centered radical.

In an attempt to rationalize this unusual result, we obtained an X-ray structure for HP-136[11] (see Figure 3 and Supporting Information). The lactone ring clearly forces the coplanarity of the attached aromatic ring, thus maximizing delocalization of the unpaired election onto this ring; the mean deviation from planarity of the lactone ring is only 0.0041 Å. This effect seems to make the two rings in HP-136 more effective than the three rings in Ph_3C in providing resonance stabilization. In the triphenylmethyl radical, steric interactions force the rings into a propeller-like structure, none of them ideally oriented for electron delocalization. Further, it is likely that the electron acceptor nature of the lactone ring further decreases the reactivity toward electrophillic dioxygen. Steric effects are unlikely to provide much hindrance at the radical site given the rather remote location of the substituents. Thus, we suggest that the antioxidant effectiveness of lactone antioxidants is largely due to the forced conformation of these systems and to electronic effects reflecting the electron-withdrawing nature of the lactone ring.

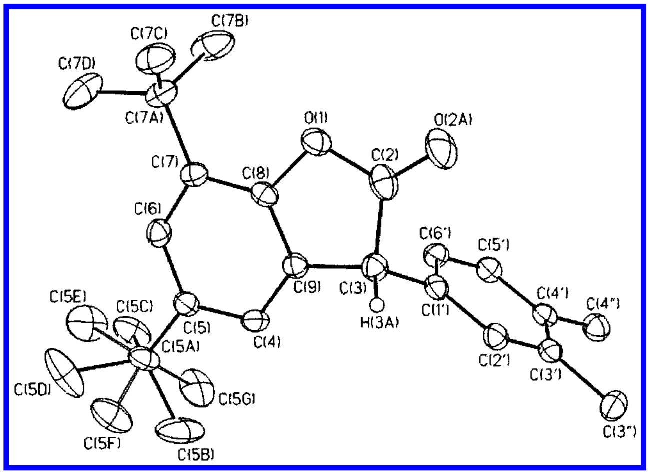
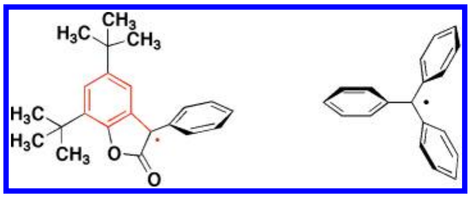


Figure 3. ORTEP diagram showing the structure of HP-136.



Thus, HP-136 is indeed an antioxidant due to the low reactivity toward oxygen of its diphenylmethyl-like radical. It is quite possible that this radical itself can act as a radical scavenger by trapping carbon-centered, or more likely, peroxyl radicals. Further, it is likely that at the operating temperatures of polymer processing the equilibrium of reaction 2 is even further displaced to the left, coincidentally optimizing the operating conditions for this antioxidant. Whether this is a unique example or whether the principles discovered in this work can be further extended in the rational design of antioxidants remains to be seen.

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Supporting Information Available: Crystal structure of HP-136. This material is available free of charge via the Internet at http://pubs.acs.org.

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