

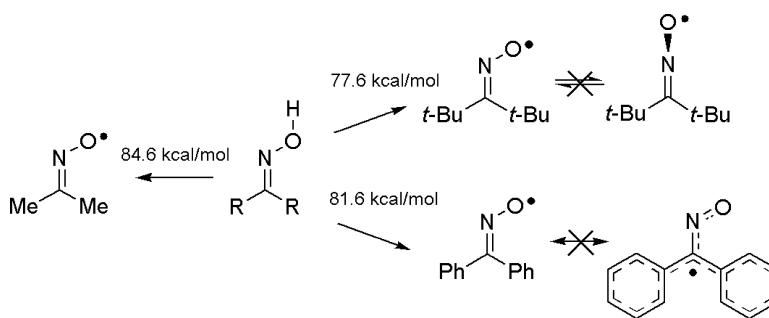
Article

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O–H Bond Dissociation Enthalpies in Oximes: Order Restored

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Abstract: The O–H bond dissociation enthalpies (BDEs) of 13 oximes, RR'C=NOH, having R and/or R' = H, alkyl, and aryl are reported. Experimental anchor points used to validate the results of theoretical calculations include (1) the O–H BDEs of (*t*-Bu)₂C=NOH, *t*-Bu(*i*-Pr)C=NOH, and *t*-Bu(1-Ad)C=NOH determined earlier from the heat released in the reaction of (*t*-Bu)₂C=NO• with (PhNH)₂ in benzene and EPR spectroscopy (Mahoney, L. R.; Mendenhall, G. D.; Ingold, K. U. *J. Am. Chem. Soc.* **1973**, *95*, 8610), all of which were decreased by 1.7 kcal/mol to reflect a revision to the heat of formation of (*E*)-azobenzene (which has significant ramifications for other BDEs) and to correct for the heat of hydrogen bonding of (*t*-Bu)₂C=NOH ($\alpha_2^H = 0.43$ measured in this work) to benzene, and (2) the measured rates of thermal decomposition of six RR'C=NOCH₂Ph at 423 or 443 K, which were used to derive O–H BDEs for the corresponding RR'C=NOH. Claims (Bordwell, F. G.; Ji, G. Z. *J. Org. Chem.* **1992**, *57*, 3019; Bordwell, F. G.; Zhang, S. *J. Am. Chem. Soc.* **1995**, *117*, 4858; and Bordwell, F. G.; Liu, W.-Z. *J. Am. Chem. Soc.* **1996**, *118*, 10819) that the O–H BDEs in mono- and diaryloximes are significantly lower than those for alkyloximes due to delocalization of the unpaired electron into the aromatic ring have always been inconsistent with the known structures of iminoxyl radicals as are the purported perpendicular structures, i.e., $\phi(C_\alpha-C=N-O^\bullet) = 90^\circ$, for sterically hindered dialkyl iminoxyl radicals. The present results confirm the 1973 conclusion that simple steric effects, not electron delocalization or dramatic geometric changes, are responsible for the rather small differences in oxime O–H BDEs.

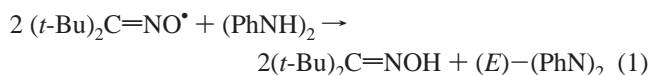
“There are also signs of a decided improvement in the bond dissociation energy situation. This has long been the scandal of kinetics, and it seems extraordinary that we are still by no means certain of many of the values for the simplest compounds. There has, however, been much accomplished in the past five years. I am by no means convinced that the present situation is as satisfactory as some workers assume, but it is certainly a great improvement.”

Introduction

The above quotation is from E. W. R. Steacie's Introductory Remarks to a 1953 Faraday Society Discussion: “The Reactivity of Free Radicals”.¹ Although most of the authors of the present paper have devoted appreciable fractions of their research to reducing some of the uncertainties in bond dissociation enthalpies (BDEs) and have employed various experimental proce-

dures and theoretical calculations to accomplish this objective,² we maintain that Steacie's words are as true today as they ever were. Indeed, they can be brought up to date simply by changing “five” to “50”! Herein, we will demonstrate that the present situation (i.e., the current literature) regarding the O–H BDEs in oximes, RR'C=NOH, could justifiably be called a “scandal”. Our work brings “a great improvement” to these BDEs that, in contrast to the literature, are now found to follow the logic dictated by the long known structures of iminoxyl radicals, RR'C=NO• (vide infra).

In 1971, the di-*tert*-butyliminoxyl radical was first isolated and characterized as a sky-blue liquid of moderate stability.^{3,4} In 1973, the O–H BDE in the parent oxime was determined by a direct calorimetric measurement of the heat released in reaction 1.⁵

[†] University of Illinois at Urbana-Champaign.[‡] National Research Council of Canada.[§] Leiden University.^{||} University of St. Andrews.[⊥] Universität Duisburg-Essen.(1) Steacie, E. W. R. *Discuss. Faraday Soc.* **1953**, *14*, 9–10.

(2) References to this rather extensive literature will be given only to those publications that are directly relevant to subjects at issue in the present article.

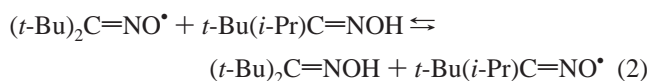
(3) Brokenshire, J. L.; Mendenhall, G. D.; Ingold, K. U. *J. Am. Chem. Soc.* **1971**, *93*, 5278–5279.(4) Mendenhall, G. D.; Ingold, K. U. *J. Am. Chem. Soc.* **1973**, *95*, 2963–2971.

Table 1. O–H BDEs in RR'C=NO–H (in kcal/mol)

R	R'	ref 5	revised ^a
<i>t</i> -Bu	<i>t</i> -Bu	80.9	79.2 ^{b,c}
<i>t</i> -Bu	<i>i</i> -Pr	84.3	82.6 ^d
<i>t</i> -Bu	1-Ad ^e	80.9 ^f	79.2 ^d

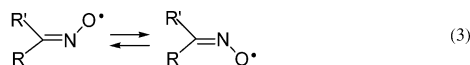
^a Revised downward by 1.7 kcal/mol; see text. ^b Calorimetric measurement. ^c This value was shown by REqEPR measurements with the DPPH• radical to be similar to the N–H BDE in DPPH₂ ($K_{\text{eq}} \approx 1$) for which a value of 79.6 kcal/mol had previously been estimated by the same calorimetric technique. See: Mahoney, L. R.; Ferris, F. C.; DaRooge, M. A. *J. Am. Chem. Soc.* **1969**, *91*, 3883–3889. ^d By REqEPR. ^e 1-Adamantyl. Di(1-adamantyl) iminoxyl is a stable, crystalline solid, but neither its O–H BDE nor (because of its crystal form) its X-ray structure has been determined. See ref 6. ^f As the text in ref 5 makes clear, the value given in Table 5 of ref 5 (viz. 80.0) is a misprint. That is, the experiment indicated that *t*-Bu(1-Ad) and (*t*-Bu)₂ oximes have the same O–H BDEs (80.9).

The O–H BDEs of two other oximes that yielded persistent iminoxyl radicals were also determined in 1973 by the radical equilibration electron paramagnetic resonance (REqEPR) technique, for example, eq 2.⁵

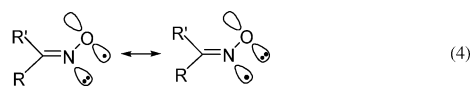


These 1973 RR'C=NO–H BDEs are summarized in Table 1.

Iminoxyl radicals were first identified in solution by Thomas⁷ in 1964 using EPR spectroscopy. He also described their *Z*–*E* isomerization:



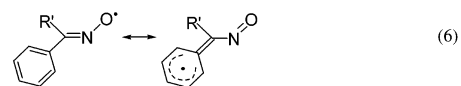
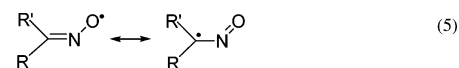
Thomas⁷ found that these radicals are characterized by a large nitrogen splitting (~28–33 G), which indicates that there is significant spin density on nitrogen⁸ in an orbital with considerable *s* character.⁹ The unpaired electron is in a π -type orbital that lies in the plane of the local molecular framework (i.e., in the nodal plane of the C=N π -bond). These radicals are therefore described as σ -radicals¹⁰ and are best represented by the canonical structures:



Thomas's early conclusion regarding the σ -structures of iminoxyl radicals (RR' = H, alkyl, aryl) has been amply confirmed by subsequent workers,^{9,11,12} and when R and R' are

different, their *E*–*Z* isomerization has been shown to be a rather slow process.^{11d,f} On this (structural) basis the following statement was made in 1973:⁵ “Replacement of a methyl group in ((Me₃C)₂C=NOH) by a hydrogen atom increases the O–H bond strength in the oximes by ca. 3.4 kcal/mol [see Table 1]. This change must be steric in origin and has been attributed to greater alkyl–alkyl and alkyl–oxygen repulsion in ((Me₃C)₂C=NOH) compared with ((Me₃C)₂C=NO•) than in tert-butyl isopropyl ketoxime compared with its iminoxy(l) radical. It's unlikely that a change of similar magnitude would accompany the replacement of additional methyls. We therefore expect that simple unhindered oximes will have O–H bond strengths of about 86 kcal/mol.”⁵

It should be noted that this 1973 statement is completely general. It is not restricted to dialkyl ketoximes and applies equally to aldoximes and aryl ketoximes, i.e., R and/or R' = H, aryl, as well as alkyl. Almost 20 years later we were, therefore, astonished by Bordwell and Ji's¹³ measurements of the O–H BDEs for a wide variety of oximes using an electrochemical (EC) method. All of Bordwell and Ji's O–H BDEs were higher, most much higher, than the ca. 86 kcal/mol that had been predicted.⁵ For example,¹³ RR'C=NO–H BDEs in kcal/mol: RR' = H, Me 98.2; Me₂ 95.8; Me, Ph(*Z*) 91.1; Me, Ph(*E*) 91.2; Ph₂ 89.0; 9-fluorenyl 87.5. The overwhelming evidence from EPR spectroscopy that iminoxyls are σ -radicals (vide supra) was totally ignored, and these O–H BDEs were interpreted in terms of π -radical structures.¹³ With a π -structure, the unpaired electron would, of course, be free to delocalize from the iminoxyl's oxygen to the sp² hybridized carbon and, hence, for R and/or R' = Ph, into the aromatic ring(s). That is,



Obviously the electron delocalization shown in eqs 5 and 6 can only occur if the unpaired electron resides in an orbital orthogonal to the local molecular framework, which is known not to be the case even for RR' = Ph₂ and 9-fluorenyl.^{7,11}

Subsequently, Bordwell and Zhang¹⁴ acknowledged the EPR-derived iminoxyl radical structures but then proceeded to ignore them. Their standard EC method was used to determine O–H BDEs for two oximes that could be checked against the early calorimetric and ESR equilibrium data⁵ (Table 1), viz.,¹⁴ (*t*-Bu)₂C=NOH = 84.2 and *t*-Bu(1-Ad)C=NOH = 81.7 kcal/mol. These BDEs were considered to be in satisfactory agreement with the earlier work, although they are neither in absolute terms nor, more significantly, in the difference in O–H BDEs for this pair of oximes, viz., 2.5 kcal/mol by EC versus 0 kcal/mol by the EPR equilibrium method⁵ (a method that is very unlikely to give BDE differences that are in error by more than 1 kcal/mol).

In 1996, Bordwell and Liu¹⁵ vigorously rejected our cautionary comments¹⁶ that the EC method (as applied by the Bordwell

(5) Mahoney, L. R.; Mendenhall, G. D.; Ingold, K. U. *J. Am. Chem. Soc.* **1973**, *95*, 8610–8614.

(6) Lindsay, D. A.; Horswill, E. C.; Davidson, D. W.; Ingold, K. U. *Can. J. Chem.* **1974**, *52*, 3554–3556.

(7) Thomas, J. R. *J. Am. Chem. Soc.* **1964**, *86*, 1446–1447.

(8) Estimated spin density on nitrogen = 41 ± 5% in an orbital whose *p/s* ratio is 6.1 ± 0.7; see ref 9.

(9) (a) Symons, M. C. R. *J. Chem. Soc.* **1965**, 2276–2277. (b) Fox, W. M.; Symons, M. C. R. *J. Chem. Soc. A* **1966**, 1503–1507.

(10) To distinguish them from the more common class of π radicals in which the unpaired electron is in an orbital perpendicular to the local molecular framework.

(11) See, for example: (a) Gilbert, B. C.; Norman, R. O. C.; Price, D. C. *Proc. Chem. Soc.* **1964**, 234. (b) Lemaire, H.; Rassat, A. *Tetrahedron Lett.* **1964**, 2245–2248. (c) Gilbert, B. C.; Norman, R. O. C. *J. Chem. Soc. B* **1966**, 86–91. (d) Dobashi, T. S.; Parker, D. R.; Grubbs, E. J. *J. Am. Chem. Soc.* **1977**, *99*, 5382–5387. (e) Mackor, A. *J. Org. Chem.* **1978**, *43*, 3241–3243. (f) Lucarini, M.; Pedulli, G. F.; Alberti, A. *J. Org. Chem.* **1994**, *59*, 1980–1983.

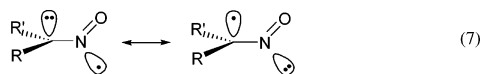
(12) Brokenshire, J. L.; Roberts, J. R.; Ingold, K. U. *J. Am. Chem. Soc.* **1972**, *94*, 7040–7049.

(13) Bordwell, F. G.; Ji, G.-Z. *J. Org. Chem.* **1992**, *57*, 3019–3025.

(14) Bordwell, F. G.; Zhang, S. *J. Am. Chem. Soc.* **1995**, *117*, 4858–4861.

group) would give O–H BDEs that were too high by up to several kcal/mol because of neglect of solvent effects, particularly hydrogen bonding. Indeed, Bordwell and Liu¹⁵ declared: “Serious solvent corrections for the BDEs obtained for these oximes are obviously not needed” because their O–H BDE for *t*-Bu(*i*-Pr)C=NOH of 86.0 kcal/mol was in “satisfactory” agreement with the 1973 value of 84.3 kcal/mol. Interestingly, their revised O–H BDE for (*t*-Bu)₂C=NOH (82.6 kcal/mol)¹⁵ was now 1.6 kcal/mol lower than the value they reported a year earlier (84.2 kcal/mol),¹⁴ and the Δ BDE(*t*-Bu(*i*-Pr)C=NO–H) – (*t*-Bu)₂C=NO–H) = 86.0 – 82.6 = 3.4 kcal/mol is identical to the 1973 Δ BDE.

For a series of dialkyl ketoximes ranging from *t*-Bu(1-Ad)C=NOH to Me₂C=NOH, the 14.1 kcal/mol increase in O–H BDEs (from 81.7 to 95.8 kcal/mol) was attributed to a decrease in steric strain in the parent oximes.¹⁴ Inconvenient EPR structural evidence was brushed aside, and a “perpendicular” structure was proposed with extensive spin density on the sp² hybridized carbon, that is,¹⁴



These “perpendicular” iminoxyl radical structures are unequivocally ruled out by EPR spectroscopy. This means *either* that a new and different explanation is required to account for the huge range in the EC-measured RR′C=NO–H BDEs *or*, more probably in our experience,¹⁷ that the reported BDEs were subject to significant errors arising from unrecognized problems in Bordwell’s experiments. These include (but are not limited to): the neglect of solvent effects (most notably hydrogen bonding) and the combination of oxidation potentials of iminoxides *estimated from irreversible cyclic voltammetry in DMSO and oxime DMSO pK_a’s* (some of which lie far above the normal pK_a range).

In earlier studies on the effects of Y-substituents on Z–X BDEs in several 4-YC₆H₄ZX families of compounds,^{17d,18,19} we have reinforced our own (non-EC) experimental measurements with theoretical calculations. Agreement between experiment and theory, particularly for BDE differences within a single family, has been excellent, and the two procedures serve, therefore, to validate one another. In the present work, theoretical calculations of O–H BDEs in a family of RR′C=NOH had to be relied on because attempts to measure some of these BDEs by photoacoustic calorimetry were unsuccessful. Fortunately, theory could be validated both by the original calorimetric data⁵ (Table 1) and by measurements of the rates of thermolysis of some RR′C=NOCH₂Ph.

Results

Revision of the 1973 O–H BDEs in Oximes.²⁰ The O–H BDE determined by calorimetry for di-*tert*-butyl ketoxime (as in eq 1) used heats of formation of *E*-azobenzene and 1,2-diphenylhydrazine in their standard states as solids of 76.49^{21a} and 52.92^{21b} kcal/mol, respectively. There have been no revisions to the heat of formation of 1,2-diphenylhydrazine. However, the heat of formation of *E*-azobenzene has been remeasured three times and found to be smaller by 2.09–2.73 kcal/mol than the original 1939 value, viz., 74.40 ± 0.81,²² 73.76 ± 0.45,²³ and 74.43 ± 0.24²⁴ kcal/mol. Since two of these values are 74.4 kcal/mol, we chose this value for our revision. We suggest that *all* O–H BDEs based upon the 1939 heat of formation of *E*-azobenzene should be adjusted downward by 2.09/2 = 1.045 ≈ 1 kcal/mol²⁵ since two hydrogen atoms are consumed for every reaction to produce *E*-azobenzene from 1,2-diphenylhydrazine.

Oximes are fairly acidic with aqueous pK_a’s of 12–13³⁰ and are known to function as hydrogen-bond donors (and hydrogen-bond acceptors).³¹ The (sterically unhindered) OH groups of oximes are therefore expected to form a hydrogen bond to benzene, which is a weak hydrogen-bond acceptor. The contribution of hydrogen bonding between the oxime and benzene to the heat generated in the calorimetric experiment can be calculated from Abraham’s empirical equation³² for determining the equilibrium constant for a 1:1 complexation in CCl₄ at room temperature between a solute with a hydrogen-bond acidity, α₂^H,³³ and a solute with a hydrogen-bond basicity of β₂^H,³⁴ viz.,³²

- (20) See footnote a, Table 1.
 (21) (a) Corruccini, R. J.; Gilbert, E. C. *J. Am. Chem. Soc.* **1939**, *61*, 2925–2927. (b) Cole, L. G.; Gilbert, E. C. *J. Am. Chem. Soc.* **1951**, *73*, 5423–5427.
 (22) Schulze, F.-W.; Patrick, H.-J.; Cammenga, H. K.; Klinge, H. Z. *Phys. Chem.* **1977**, *107*, 1–19.
 (23) Dias, A. R.; Minas Da Piedade, M. E.; Martinho Simões, J. A.; Simoni, J. A.; Teixeira, C.; Diogo, H. P.; Yang, M.-Y.; Pilcher, G. *J. Chem. Thermodyn.* **1992**, *24*, 439–447.
 (24) Steele, W. V.; Chirico, R. D.; Knipmeyer, S. E.; Nguyen, A.; Smith, N. K. *J. Chem. Eng. Data* **1996**, *41*, 1285–1302.
 (25) This revision has important implications since the calorimetric O–H BDE in 2,4,6-tri-*tert*-butylphenol of 81.24 kcal/mol²⁶ has been used as the standard for all BDEs determined by the REqEPR technique,^{17d,27} and hence, all of these BDEs should be revised downward by 1 kcal/mol (and even lower for many phenols because of H-bonding to the benzene solvent used for REqEPR measurements).²⁸ Interestingly, the 1 kcal/mol downward revision of the O–H BDE in phenol and α-tocopherol yields values of 87.3 and 77.3 kcal/mol, respectively, in full agreement with the results obtained by photoacoustic calorimetry.^{16,29}
 (26) Mahoney, L. R.; Ferris, F. C.; DaRooge, M. A. *J. Am. Chem. Soc.* **1969**, *91*, 3883–3889.
 (27) (a) Lucarini, M.; Pedulli, G. F.; Cipollone, M. *J. Org. Chem.* **1994**, *59*, 5063–5070. (b) Lucarini, M.; Pedrielli, P.; Pedulli, G. F.; Cabiddu, S.; Fattuoni, C. *J. Org. Chem.* **1996**, *61*, 9259–9263. (c) Lucarini, M.; Pedrielli, P.; Pedulli, G. F.; Valgimigli, L.; Gignies, D.; Tordo, P. *J. Am. Chem. Soc.* **1999**, *121*, 11546–11553. (d) Pratt, D. A.; DiLabio, G. A.; Brigatti, G.; Pedulli, G. F.; Valgimigli, L. *J. Am. Chem. Soc.* **2001**, *123*, 4625–4626. (e) Valgimigli, L.; Brigatti, G.; Pedulli, G. F.; DiLabio, G. A.; Mastragostino, M.; Arbizzani, C.; Pratt, D. A. *Chem.–Eur. J.* **2003**, *9*, 4997–5010.
 (28) These corrections to REqEPR-derived BDEs will be detailed in a forthcoming article.
 (29) Wayner, D. D. M.; Luszyk, E.; Ingold, K. U.; Mulder, P. *J. Org. Chem.* **1996**, *61*, 6430–6433.
 (30) See, for example: (a) Brady, O. L.; Goldstein, R. F. *J. Chem. Soc.* **1926**, 1918–1924. (b) King, C. V.; Marion, A. P. *J. Am. Chem. Soc.* **1944**, *66*, 977–980. (c) Bell, R. P.; Higginson, W. C. E. *Proc. R. Soc. London* **1949**, *197A*, 141–149.
 (31) See, for example: Hoogesteger, F. J.; Jenneskens, L. W.; Kooijman, H.; Veldman, N.; Spek, A. L. *Tetrahedron* **1996**, *52*, 1773–1784.
 (32) Abraham, M. H.; Grellier, P. L.; Prior, D. V.; Taft, R. W.; Morris, J. J.; Taylor, P. J.; Laurence, C.; Berthelot, M.; Doherty, R. M.; Kamlet, M. J.; Abboud, J.-L. M.; Sraidi, K.; Guihéneuf, G. *J. Am. Chem. Soc.* **1988**, *110*, 8534–8536.
 (33) Abraham, M. H.; Grellier, P. L.; Prior, D. V.; Duce, P. P.; Morris, J. J.; Taylor, P. J. *J. Chem. Soc., Perkins Trans. 2* **1989**, 699–711.

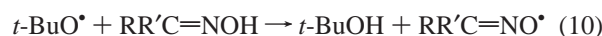
- (15) Bordwell, F. G.; Liu, W.-Z. *J. Am. Chem. Soc.* **1996**, *118*, 10819–10823.
 (16) Wayner, D. D. M.; Luszyk, E.; Pagé, D.; Ingold, K. U.; Mulder, P.; Laarhoven, L. J. J.; Aldrich, H. S. *J. Am. Chem. Soc.* **1995**, *117*, 8737–8744.
 (17) The sources of error we have identified in Bordwell et al.’s EC-measured O–H BDEs for phenols and N–H BDEs for anilines have been described: (a) Reference 16. (b) Snelgrove, D. W.; Luszyk, J.; Banks, J. T.; Mulder, P.; Ingold, K. U. *J. Am. Chem. Soc.* **2001**, *123*, 469–477. (c) MacFaul, P. A.; Wayner, D. D. M.; Ingold, K. U. *J. Org. Chem.* **1997**, *62*, 3413–3414. (d) Pratt, D. A.; DiLabio, G. A.; Valgimigli, L.; Pedulli, G. F.; Ingold, K. U. *J. Am. Chem. Soc.* **2002**, *124*, 11085–11092.
 (18) Pratt, D. A.; Wright, J. S.; Ingold, K. U. *J. Am. Chem. Soc.* **1999**, *121*, 4877–4882.
 (19) Pratt, D. A.; de Heer, M. I.; Mulder, P.; Ingold, K. U. *J. Am. Chem. Soc.* **2001**, *123*, 5518–5526.

$$\log(K/M^{-1}) = 7.354\alpha_2^H\beta_2^H - 1.094 \quad (8)$$

Since α_2^H values for oximes have never been reported, the value for one of the more hindered oximes, di-*tert*-butyl ketoxime, was determined in the usual way using two strong (and calibrated)³³ bases (see Experimental Section). In CCl₄, di-*tert*-butyl ketoxime self-associates at concentrations >2.3 mM, which demonstrates that the O–H moiety is not sterically protected and that its α_2^H value should apply to most other oximes. From the equilibrium constants for 1:1 complex formation of this oxime with DMSO ($\beta_2^H = 0.78$)³⁴ and acetone ($\beta_2^H = 0.50$),³⁴ an α_2^H value of 0.43 was obtained. Using this value, along with the literature β_2^H value for benzene (0.15),³⁴ we calculate an equilibrium constant for the 1:1 complexation between the solute and solvent of 0.240 M⁻¹. This means that the ratio of hydrogen-bonded oxime to free oxime in benzene is 2.69:1, corresponding to 72.9% of the oxime in the hydrogen-bonded form. The value of the equilibrium constant, together with an entropy change of –6 cal/mol K,³⁵ leads to a ΔH for hydrogen-bond formation of –0.94 kcal/mol. Thus, in the original calorimetric experiment (eq 1), 72.9% of the oxime formed was hydrogen-bonded to the benzene, and this added $0.729 \times 0.94 \times 2 = 1.4$ kcal/mol to the overall heat produced in the reaction.

Since the heat of reaction for eq 1 is too high by 1.4 kcal/mol because of H-bonding of the product oxime to benzene, the real O–H BDE in di-*tert*-butyl ketoxime is 0.7 kcal/mol lower. For RR' = *t*-Bu, *i*-Ad and *t*-Bu, *i*-Pr, the values for the BDE(O–H) must also be lowered by 0.7 kcal/mol. Thus, correcting for the revised heat of formation of *E*-azobenzene and for hydrogen bonding of the oxime product requires a downward revision of these three “benchmark” oxime O–H BDEs of –1.0 + (–0.7) = –1.7 kcal/mol (Table 1).

Attempted Measurements of O–H BDEs in Oximes by Photoacoustic Calorimetry (PAC). This procedure has been successfully applied by some of us to measurements of O–H BDEs in phenols^{16,29} and N–H BDEs in aromatic amines.^{17c} Reliable gas-phase BDEs can be obtained provided the proper corrections for quantum yields, heats of solution of the reactants and products, etc., are made.¹⁶ The PAC technique we employed^{16,17c,29,36} requires the irradiation of a solution containing the oxime and di-*tert*-butyl peroxide with the pulses from a nitrogen laser (337 nm). This produces *tert*-butoxyl radicals “instantaneously”, eq 9, which subsequently abstract a hydrogen atom from the oxime, eq 10.



The kinetic requirement is that reaction 10 be complete in less than 100 ns so that heat is evolved on a time scale that is much shorter than the intrinsic response time of the microphone (ca. 2 μ s). That is, $k_{10} \times [\text{RR}'\text{C}=\text{NOH}]$ must be $>10^7 \text{ s}^{-1}$, and since the substrates self-associate at concentrations slightly above 2 mM (vide supra) it would be necessary for k_{10} to be $\sim 5 \times 10^9 \text{ M}^{-1} \text{ s}^{-1}$.

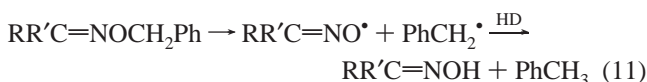
Table 2. Rate Constants for H-Atom Abstraction from Some Oximes and Phenols by *tert*-Alkoxy Radicals in Benzene at Ambient Temperatures Measured by Laser Flash Photolysis

substrate	k (M ⁻¹ s ⁻¹)	O–H BDE kcal/mol
Me ₂ C=NOH	3.2×10^6	84.6 ^a
(<i>i</i> -Pr) ₂ C=NOH	6.5×10^6	82.7 ^a
(<i>t</i> -Bu) ₂ C=NOH	4.2×10^7	77.6 ^a
PhOH	2.8×10^{8b}	87.3 ^c
α -tocopherol	3.1×10^{9b}	77.3 ^d

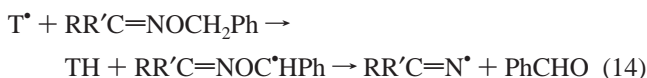
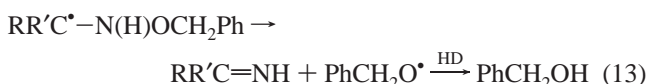
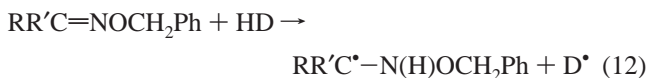
^a This work; see Table 7. ^b Values taken from ref 17b. ^c Reference 16. ^d Reference 29.

Measurements of k_{10} by laser flash photolysis in the usual manner^{17b} showed that these rate constants are much too small for PAC experiments. Indeed, they are roughly 2 orders of magnitude slower than the rate constants for abstraction of hydrogen from phenols having comparable O–H BDEs (Table 2). Unexpectedly slow rates of H-atom abstraction from oximes have been observed previously.³⁷ The reason for the slowness of such reactions has now been identified and will be reported elsewhere.³⁸ Since the measurement of O–H BDEs in RR'C=NOH by PAC proved to be impossible, we measured the rates of thermolysis of six RR'C=NOCH₂Ph.

Thermolyses of O–Benzyl Oxime Ethers. We have previously studied the effect of para-substituents, Y, on O–C BDEs in 4-YC₆H₄OCH₂Ph and 4-YC₆H₄CH₂OC₆H₅ by measuring their rates of thermal decomposition in a very good hydrogen donor (HD) solvent, 9,10-dihydroanthracene (DHA).¹⁹ The same experimental method was applied in an attempt to measure O–C BDEs in 11 oxime *O*-benzyl ethers, RR'C=NOCH₂Ph using DHA, 9,10-dihydrophenanthrene (DHP), and tetralin (TH) as HDs,³⁹ that is, reaction 11. However, at 150 °C it was obvious from the products, viz., imine and benzyl alcohol in all cases (plus benzaldehyde in tetralin), that other reactions were occurring.



Either there was a strong preference for N–O bond cleavage over the expected O–C cleavage or there was an extensive reverse radical disproportionation (RRD)-induced decomposition⁴⁰ (reaction 12 and 13), and that in tetralin an induced decomposition also took place (reaction 14).



That RRD-induced decomposition was important was confirmed by the decrease in the rates of decomposition of all the

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Table 3. Observed Rate Constants for Disappearance of RR'C=NOCH₂Ph in Degassed *tert*-Butylbenzene at the Given Temperature, Estimated Activation Enthalpies for Thermal O–C Bond Scission, E_a , and Calculated Gas Phase O–C and N–O BDEs at 298 K^a

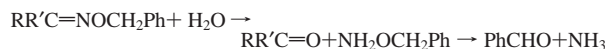
R	R'	T/K	10 ⁸ k/s ⁻¹	E_a^b	O–C BDE ^{c,d}	N–O BDE ^{c,d}	N–H BDE ^{c,e}
Me	Me	—	—	—	48.6	51.2	90.2
Ph	Ph	443	0.42	47.9	45.7	50.7	91.7
9-fluorenyl		443	0.61	47.5	46.4	53.6	92.4
Me ₂ CH	Me ₂ CH	443	8.9	45.2	46.8	49.3	89.6
Me ₃ C	Me ₂ CH	443	13.2	44.8	45.9	48.9	88.0
Me ₃ C	Me ₃ C	443	23.7	44.3	41.9	43.8	86.5
Me ₃ C	<i>E</i> -1-Ad	423	17.7	42.5	41.6	43.1	86.1
Me ₃ C	<i>Z</i> -1-Ad	423	34.8	42.0	40.9	42.5	86.2

^a Calculated gas-phase N–H BDEs at 298 K for RR'C=NH are presented for comparison. ^b Calculated E_a in kcal/mol assuming $\log(A/s^{-1}) = 15.2$. ^c Calculated BDEs in kcal/mol. ^d (RO)B3P86/6-311G(d,p)/(U)B3P86/6-311G(d,p) as in ref 46. ^e (RO)B3LYP/6-311+G(2d,2p)/(U)B3LYP/6-31G(d) as in ref 47.

O-benzyl ethers as the HD abilities of the solvents decreased from DHA, to DHP, to TH.³⁹ To circumvent these induced decomposition reactions, we turned to the very poor HD solvent, *tert*-butylbenzene. Rate constants were determined for the decomposition of *t*-Bu(1-Ad)C=NOCH₂Ph at 423 K and for five other RR'C=NOCH₂Ph at 443 K (see Table 3). All the reactions were extremely slow,⁴¹ and the samples (which had been sealed under vacuum in glass ampules)^{19,39} had to be heated for many weeks for there to be sufficient decomposition of the *O*-benzyl ethers for the decomposition rate constants to be calculated.^{42,43} Since good linear correlations of $\ln([\text{oxime}]_{t=0}/[\text{oxime}]_{t=t})$ versus reaction time were obtained for all RR'C=NOCH₂Ph studied (see Supporting Information), any radical chain or other types of induced decomposition reactions are likely to be of little or no importance even at this high temperature.⁴⁴

Interestingly, the *E*- and *Z*-isomers of *t*-Bu(1-Ad)C=NOCH₂Ph (not separated and identified only by their different thermal stabilities) did not equilibrate and had rate constants for decomposition of $1.77 \times 10^{-7} \text{ s}^{-1}$ and $3.48 \times 10^{-7} \text{ s}^{-1}$ at 423 K. Assuming that the Arrhenius pre-exponential factor for reaction 11 is the same as that for the analogous reaction: PhOCH₂Ph → PhO• + PhCH₂•, viz.,¹⁹ $\log(A/s^{-1}) = 15.2$,⁴⁵ the two measured rate constants yield $E_a \approx 42.5$ and 42.0 kcal/mol for O–C bond homolysis. These estimated activation enthalpies are in very good agreement with the calculated O–C BDEs of 41.6 and 40.9 kcal/mol for the *E*- and *Z*-isomers of *t*-Bu(1-Ad)C=NOCH₂Ph, respectively (see Table 3). Furthermore, these estimated E_a values can be combined with the known difference

- (41) Since 443 K is just above the boiling point of *tert*-butylbenzene, reaction times were not shortened by raising the temperature for reasons of safety.
 (42) Benzaldehyde was formed at an early stage in the decomposition of the five RR'C=NOCH₂Ph studied at 443 K. We have interpreted this as the retrosynthesis of the oxime *O*-benzyl ethers with residual water present in the reaction ampules:



In the data analysis, a pre-equilibration time was used to compensate for this feature.

- (43) Product identification and quantification^{19,39} was not pursued in the present work because it is well-established that the room-temperature bimolecular self-reactions of iminoxyl radicals produce mixtures of oxygen-to-carbon, oxygen-to-nitrogen, and nitrogen-to-nitrogen coupled dimers.^{4,12,44} Even at room temperature these dimers (RRCNO)₂ break down to form an amazing array of small, thermally more stable products, including N₂, N₂O, RCN, RRC=NH, RRC=O, RRC=NOH, and even RRNO•.^{4,12} The probable mechanisms by which these compounds are formed have been described.¹² At least some of these products were present after heating the *O*-benzyl oxime ethers to 443 K for many weeks, but since they provide no useful information they will be ignored henceforth.
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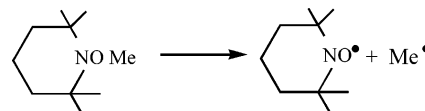
between the O–H BDE for C₆H₅OH and the O–CH₂Ph BDE for C₆H₅OCH₂Ph, viz.,¹⁹ 34.5 kcal/mol, to obtain O–H BDEs of 77.0 and 76.5 kcal/mol for *t*-Bu(1-Ad)C=NO–H, values which are in the most gratifying agreement with our recommended O–H BDEs of 77.2 and 76.9 kcal/mol (vide infra).

The activation enthalpies for O–C cleavage for the other five *O*-benzyl oxime ethers were calculated from the measured rate constants at 443 K, again assuming that $\log(A/s^{-1}) = 15.2$.^{19,45} These E_a values are in satisfactory agreement with the calculated O–C BDEs (see Table 3). The addition of 34.5 kcal/mol to E_a gives estimated O–H BDEs for the five corresponding oximes that are also in satisfactory agreement with our recommended values (vide infra).

For completeness, Table 3 also includes calculated N–O BDEs for the RR'C=NOCH₂Ph compounds and calculated N–H BDEs for the corresponding imines. For each *O*-benzyl ether the N–O BDE is a few kcal/mol larger than the O–C BDE, a result fully consistent with our product and kinetic work in HD solvents.³⁹ For each *O*-benzyl ether/imine pair of compounds the N–H BDE is 40 ± 1 kcal/mol stronger than the N–O BDE except for the two most sterically congested pairs where this difference rises to 42.7 kcal/mol ((*t*-Bu)₂) and 43.0/43.7 kcal/mol (*E/Z-t*-Bu(1-Ad)), indicating that bond-weakening steric effects are larger for the N–O bond than for the N–H bond, as expected. The effects of the RR' groups on these N–O and N–H bonds have been discussed elsewhere.⁴⁸

Theoretical Calculations of O–H BDEs in Oximes. In our theoretical studies, we first established a good reference O–H BDE value for acetone oxime against which all of the other calculated oxime O–H BDEs could be scaled. In particular, we wished to determine whether the O–H BDE in acetone oxime was ca. 84 kcal/mol (estimate from ref 5 as modified herein) or 96 kcal/mol as Bordwell reported.¹³ The results of our calculations of the O–H BDE in acetone oxime (RR' = Me₂) are presented in Table 4. In addition to a model DFT approach,⁴⁷ we include the BDEs calculated by some of the

- (45) Similarly, for the O–C bond homolysis:



- $\log(A/s^{-1}) = 15.3$. See Ciriano, M. V.; Korth, H.-G.; van Scheppingen, W. B.; Mulder, P. *J. Am. Chem. Soc.* **1999**, *121*, 6375–6381.
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Table 4. Gas Phase O–H BDE in Acetone Oxime Calculated by a Variety of Methods at 298 K in kcal/mol

method	BDE
G3MP2	86.5
G3	85.9
CBS-QB3	85.1
CBS-APNO	84.6
DFT ^a	82.6

^a DFT = (RO)B3LYP/6-311+G(2d,2p)/(U)B3LYP/6-31G(d) as in ref 47.

more common, so-called, high-accuracy model chemistries, viz., G3MP2,⁴⁹ G3,⁵⁰ CBS-QB3,⁵¹ and CBS-APNO.⁵²

To study changes in O–H BDEs in RR'C=NOH induced by different R and R' groups, we calculated each O–H BDE using the same model DFT approach⁴⁷ as that used in Table 4. The O–H BDEs for some of the smaller oximes were also calculated using the complete basis set approach as implemented in the CBS-QB3 compound method of Petersson and co-workers,⁵¹ which is the highest level of theory possible for molecules of even their modest size. The results are presented in Table 5. Some relevant (vide infra) structures and relative energies of the di-*tert*-butyl iminoxyl radical are shown in Figure 1. Geometrical data for the oximes of acetone, acetophenone, benzophenone, and di-*tert*-butyl ketone and for their respective iminoxyl radicals are given in Table 6.

Discussion

First, we should point out that the calculated minimum energy structures of *E*- and *Z*-acetophenone oximes and di-*tert*-butyl ketoxime are in good agreement with their published X-ray structures (see Table 6). This gives us confidence in the validity of the calculated minimum energy structures of the iminoxyl radicals in their ground electronic states. These calculations confirm that iminoxyl radicals do not have substantial spin density at the sp²-hybridized carbon, that is, the canonical structures shown in eqs 5 and 6 are not consistent with known facts. Instead, and in excellent agreement with estimates from EPR spectroscopy,^{8,9} we find that 42–45% of the spin is on the nitrogen atom with virtually all of the rest on the oxygen. Hence, there can be no spin delocalization into the phenyl rings in the benzaldehyde, acetophenone, benzophenone, and fluorenone iminoxyl radicals, results which are only consistent with iminoxyls being σ radicals (as shown by the canonical structures in eq 4).

Second, the “perpendicular” structures of iminoxyl radicals that maintain their σ -structure (as shown by the canonical structures in eq 7) are not energy minima. In fact, they are not even transition states on the surface that connects the *E*- and *Z*-isomers of asymmetric iminoxyls. The only way to reach a stationary point corresponding to a “perpendicular” structure for the iminoxyl radicals is to constrain the CNO bond angle (e.g., 135.8° for RR' = *t*-Bu₂; 133.6° for RR' = Me₂) and the two CCNO dihedral angles (to 90°), which leads to structures that are 27.7 and 32.6 kcal/mol higher in energy, respectively,

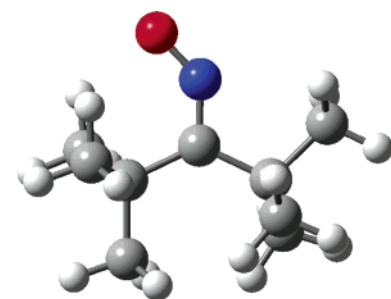
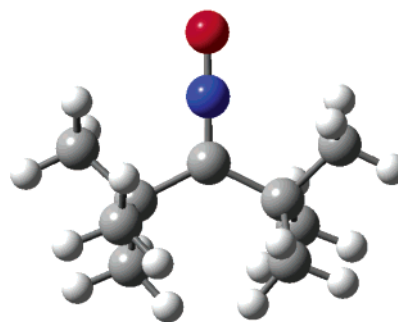
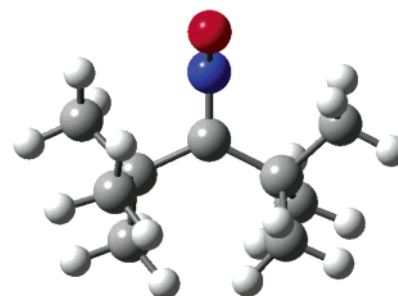
A. $\Delta E_e = 0.0$ kcal/molB. $\Delta E_e = 10.4$ kcal/molC. $\Delta E_e = 27.7$ kcal/mol

Figure 1. (RO)B3LYP/6-311+G(2d,2p)/(U)B3LYP/6-31G(d) Structures and relative energies of three geometries of the di-*tert*-butyl iminoxyl radical: A, minimum; B, linearized; C, perpendicular.

than the minimum energy structures. Furthermore, it is the linearized iminoxyl (CNO angle = 180°) that is the transition state between the *E*- and *Z*-isomers. The barrier to the isomerization is 13.1 kcal/mol for RR' = Me₂. This drops to 10.4 kcal/mol for RR' = *t*-Bu₂, in good agreement with an experimental value of 9.6 kcal/mol calculated from NMR data for the exact same iminoxyl radical.⁵³ Using INDO calculations, Alberti et al.⁵⁴ had previously obtained 8.9 and 36.5 kcal/mol for the barriers to isomerization of the iminoxyl of acrolein (R = vinyl, R' = H) by linearization and rotation, respectively.

Calculated O–H BDEs for acetone oxime by the four compound methods in Table 4 show a nice convergence upon increasing the complexity of the calculation to the CBS-APNO result of 84.6 kcal/mol. The highest result, 86.5 kcal/mol by G3MP2, is still 9.3 kcal/mol less than Bordwell's 95.8 kcal/mol.¹³ Most gratifyingly, the CBS-APNO result of 84.6 kcal/mol is essentially identical to the (modified) 1973 prediction

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Table 5. Gas-Phase O–H BDEs of Oximes (RR'C=NOH) at 298 K in kcal/mol^a

R	R'	calculated BDE		experimental BDE	
		DFT ^b	CBS-QB3	EC ^c	other
H	H	81.5 (–1.1)	83.4 (–1.7)	–	–
H	Me	83.0 (0.4)	85.0 (–0.1)	98.2 (2.4)	–
		<i>80.6 (–2.0)^d</i>	<i>83.7 (–1.4)^d</i>		
H	CF ₃	82.4 (–0.2)	84.5 (–0.6)	–	–
		<i>80.8 (–1.8)^d</i>	<i>83.3 (–1.8)^d</i>		
Me	Me	82.6 (0.0)	85.1 (0.0)	95.8 (0.0)	84.3 ^{e,f}
H	Ph	81.9 (–0.7)	85.3 (0.2)	86.9 (–8.9)	–
		<i>77.4 (–5.2)^d</i>	<i>81.6 (–3.5)^d</i>		
Me	Ph	80.8 (–1.8)	84.5 (–0.6)	91.2 (–4.6)	–
		<i>78.1 (–4.5)^d</i>	<i>81.7 (–3.4)^d</i>		
Ph	Ph	79.6 (–3.0)	–	89.0 (–6.8)	82.4 ^g
9-fluorenyl		79.8 (–2.8)	–	87.5 (–8.3)	82.0 ^g
Et	Et	81.8 (–0.8)	84.2 (–0.9)	–	–
<i>i</i> -Pr	<i>i</i> -Pr	80.7 (–1.9)	82.5 (–2.6)	87.7 (–8.1)	79.7 ^g
<i>t</i> -Bu	<i>i</i> -Pr	79.5 (–3.1)	–	86.0 (–9.8)	79.3, ^g 82.6 ^{f,h}
<i>t</i> -Bu	<i>t</i> -Bu	75.6 (–7.0)	–	84.2 (–11.6) ^{i,j}	78.8, ^g 79.2 ^{f,k}
<i>t</i> -Bu	1-Ad	75.2 (–7.4)	–	81.7 (–14.1)	77.0, ^g 79.2 ^{f,h}
		<i>74.9 (–7.7)^d</i>			76.5 ^{d,g}

^a Differences from acetone oxime (Δ BDEs) are given in parentheses. ^b DFT=(RO)B3LYP/6-311+G(2d,2p)/(U)B3LYP/6-31G(d) as in ref 47. ^c EC = electrochemically derived values from refs 13–15. ^d Values in italics correspond to the *Z*-isomer for both the oxime and iminoxyl radical (highest priority cis to oxygen). ^e Predicted value from ref 5. ^f Reduced by 1.7 kcal/mol; see text. ^g Thermolysis of *O*-benzyl oxime ether in *tert*-butylbenzene, Table 3's E_a + 34.5 (this work). See text. ^h REqEPR from ref 5. ⁱ Reference 14. ^j This is given as 82.6 in ref 15 (see text). ^k Calorimetric value from ref 5.

Table 6. Calculated Bond Lengths (Å) and Angles (Degrees) for Some Oximes and Their Iminoxyl Radicals and Measured (X-ray) Values in Bold Face Where Available

	$r(\text{C–CN})^a$	$r(\text{C–N})^b$	$r(\text{C=N})$	$r(\text{N–O})$	$\angle(\text{CCC})$	$\angle(\text{CCN})^a$	$\angle(\text{CCN})^b$	$\angle(\text{CNO})$	$\angle(\text{PhCC})^c$
Me ₂ CNOH	1.5041	1.5074	1.2822	1.4158	119.7	116.4	123.9	111.0	
Me ₂ CNO•	1.5026	1.5083	1.2859	1.2392	120.2	118.5	121.4	133.6	
<i>E</i>-Ph(Me)CNOH^d	1.480	1.492	1.173	1.427	122.48	117.88	118.42	121.05	0.25
<i>E</i>-Ph(Me)CNOH^d	1.487	1.486	1.284	1.403	121.44	115.36	123.21	112.44	1.46
<i>E</i> -Ph(Me)CNOH	1.4874	1.5084	1.2884	1.4041	119.95	115.99	124.06	113.07	0
<i>E</i> -Ph(Me)CNO•	1.4750	1.5114	1.2939	1.2345	122.12	118.31	119.57	133.64	0
<i>Z</i>-Ph(Me)CNOH^d	1.484	1.522	1.259	1.426	117.53	130.89	111.42	113.10	26.41
<i>Z</i>-Ph(Me)CNOH^d	1.427	1.524	1.274	1.379	118.56	127.42	114.00	114.56	44.91
<i>Z</i> -Ph(Me)CNOH	1.4883	1.5136	1.2892	1.4074	118.72	128.26	113.03	114.38	31.58
<i>Z</i> -Ph(Me)CNO•	1.4784	1.5083	1.2947	1.2361	121.64	122.73	115.62	135.06	0
Ph ₂ CNOH	1.4899	1.4929	1.2900	1.4000	119.8	115.1	125.2	113.3	26.0 ^a
Ph ₂ CNO•	1.4857	1.4861	1.2991	1.2346	123.1	115.7	121.3	134.5	26.8 ^a
(Me₃C)₂CNOH^e	1.536	1.553	1.282	1.415	125.0	111.9	123.1	116.6	
(Me ₃ C) ₂ CNOH	1.5581	1.5582	1.2870	1.4129	125.8	110.7	123.4	116.2	
(Me ₃ C) ₂ CNO•	1.5450	1.5607	1.2892	1.2395	128.9	114.3	116.6	135.8	

^a (*E*) to O. ^b (*Z*) to O. ^c Angle between phenyl ring plane and oxime plane. ^d Original work: Gieren, A.; Ruiz-Perez, C. *Chem.-Ztg.* **1986**, *110*, 73, revised by Herbstein, F. H.; Marsh, R. E. *Acta Crystallogr.* **1998**, *B54*, 677–686 from the Cambridge Structure Data Base. Two molecules with slightly different structures are present in the unit cell. ^e Reference 14.

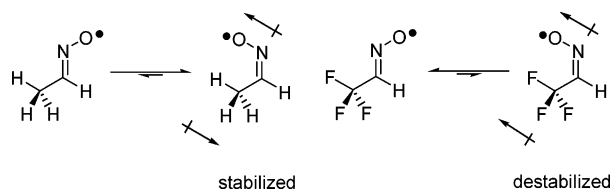
of ca. 86 – 1.7 = 84.3 kcal/mol.⁵ That the DFT model underestimates the O–H BDE relative to the CBS-APNO result by 2 kcal/mol was expected from recent work.⁵⁵

There are some interesting trends in the O–H BDEs among the first five oximes listed in Table 5. For clarity we discuss only the CBS-QB3 results, but it should be pointed out that the DFT results provide the same trends. Replacement of the *E*-hydrogen in formaldoxime by a methyl (or phenyl) group to make *E*-acetaldehyde oxime (or *E*-benzaldehyde oxime) increases the O–H BDE by 1.6 (or 1.9) kcal/mol, while replacement of the *Z*-hydrogen by a methyl (or phenyl) group to make the *Z*-isomers increases the O–H BDE by only 0.3 (or decreases it by 1.8) kcal/mol. These differences arise, in part, from steric destabilization of the *Z*-aldoximes by 0.5 (Me) and 2.0 (Ph) kcal/mol. More interestingly, the *Z*-iminoxyl radicals are calculated to be *stabilized* by 0.8 (Me) and 1.7 (Ph) kcal/

mol relative to their *E*-isomers. These calculated stereochemical preferences of RCH=NO• are surprising but are fully supported by EPR spectroscopic studies. For example, Alberti et al.⁵⁴ have shown that only *Z*-PhCH=NO• can be detected upon photolysis of di-*tert*-butyl peroxide with a mixture of *Z*- and *E*-benzaloxime in *tert*-butylbenzene at room temperature. This result was attributed to a combination of π -nonbonded interactions, H-bonding of the ortho hydrogen to the iminoxyl oxygen, and σ -conjugative interactions. However, we found none of these suggested interactions between the Ph and NO• groups to be very convincing. We considered it more probable that the *Z*-RCH=NO• preference is a consequence of dipole–dipole interactions, and this idea was explored with calculations on CF₃CH=NOH and CF₃CH=NO•. As is the case with CH₃CH=NOH, replacement of the *Z*-hydrogen in formaldoxime with a CF₃ very slightly decreases the O–H BDE (0.1 kcal/mol), whereas replacement of the *E*-hydrogen increases the BDE by 1.1 kcal/mol (see Table 5). The *Z*-isomer of CF₃CH=NOH is destabilized (by 2.0 kcal/mol) relative to the *E*-isomer (like

(55) See, for example: (a) Wijtmans, M.; Pratt, D. A.; Valgimigli, L.; DiLabio, G. A.; Pedulli, G. F.; Porter, N. A. *Angew. Chem., Int. Ed.* **2003**, *42*, 4370–4373. (b) Pratt, D. A.; DiLabio, G. A.; Brigati, G.; Pedulli, G. F.; Valgimigli, L. *J. Am. Chem. Soc.* **2001**, *123*, 4625–4626.

$Z\text{-CH}_3\text{CH}=\text{NOH}$ vs $E\text{-CH}_3\text{CH}=\text{NOH}$). However, in contrast to $Z/E\text{-CH}_3\text{CH}=\text{NO}^\bullet$, the Z -isomer of $\text{CF}_3\text{CH}=\text{NO}^\bullet$ was *destabilized* (by 0.8 kcal/mol) relative to its E -isomer. These results are consistent with favorable and unfavorable interactions of the $\text{N} \rightarrow \text{O}$ dipole with the $\text{H} \rightarrow \text{C}$ and $\text{C} \rightarrow \text{F}$ dipoles in these iminoxyl radicals:



Replacement of the aldehydic H in E - and $Z\text{-CH}_3\text{CH}=\text{NOH}$ by a Me group increases the O–H BDE by 0.1 and 1.4 kcal/mol, respectively, to give an overall O–H $\Delta\text{BDE}(\text{H}_2\text{C}=\text{NOH} - \text{Me}_2\text{C}=\text{NOH})$ from additivity of $-1.4 + -0.1 = -1.5$ kcal/mol (Table 5), while direct calculation gives -1.7 kcal/mol. Again, replacement of the Z -aldehydic H in $E\text{-CH}_3\text{CH}=\text{NOH}$ by Me destabilizes $\text{Me}_2\text{C}=\text{NOH}$ but stabilizes the radical, and these two effects roughly cancel out to give approximately equal O–H BDEs for acetone oxime and E -acetaldehyde oxime. The bond strengthening due to the E -methyl group must result from hyperconjugation of a linear combination of $\sigma_{\text{C-H}}$ orbitals with the correct symmetry to overlap with the $\pi_{\text{C=N}^*}$ orbital.

Comparison of $\text{RR}' = \text{Me}_2$ with aromatic R and R' groups gives DFT ΔBDEs ($\text{Me}_2\text{C}=\text{NOH} - \text{RR}'\text{C}=\text{NOH}$) of -0.7 , -1.8 , and -3.0 kcal/mol for $\text{RR}' = E\text{-H, Ph, } E\text{-Me, Ph, and Ph}_2$, respectively (see Table 5), values that are in very poor agreement with Bordwell and Ji's¹³ ΔBDEs of -8.9 , -4.6 , and -6.8 kcal/mol, respectively. To confirm these DFT-calculated ΔBDEs , the O–H BDEs in benzaldehyde and acetophenone oxime were also calculated at the CBS-QB3 level, which yielded ΔBDEs of 0.2 and -0.6 kcal/mol, respectively, values that are even smaller than the DFT-calculated ΔBDEs by 0.9 and 1.2 kcal/mol, respectively.

The calculations clearly show that the decrease in O–H BDE in $\text{RR}'\text{C}=\text{NOH}$ induced by $\text{RR}' =$ two bulky alkyl groups relative to $\text{RR}' = \text{Me}_2$ is due to the increase in steric repulsion between R (or R') and O, and between R and R' as suggested in 1973.⁵ The importance of steric hindrance is indicated by the calculated bond lengths and angles for R_2CNOH and $\text{R}_2\text{CNO}^\bullet$ with R = Me, Ph, and $t\text{-Bu}$ (Table 6). For example, comparing Me_2CNOH with $\text{Me}_2\text{CNO}^\bullet$, the CCC angle increases by 0.5° (119.7° to 120.2°) and the CNO angle increases by 22.6° (111.0° to 133.6°), whereas for the $(t\text{-Bu})_2\text{CNOH}/(t\text{-Bu})_2\text{CNO}^\bullet$ couple the CCC angle increases by 3.1° (125.8° to 128.9°) and the CNO angle increases by 19.6° (116.2° to 135.8°). The larger CCC and CNO angles in $(t\text{-Bu})_2\text{CNOH}$ compared with Me_2CNOH , together with the greater expansions of these angles on forming $(t\text{-Bu})_2\text{CNO}^\bullet$, indicate a considerably greater relief of steric strain for $(t\text{-Bu})_2\text{CNOH} \rightarrow (t\text{-Bu})_2\text{CNO}^\bullet$ than for $\text{Me}_2\text{CNOH} \rightarrow \text{Me}_2\text{CNO}^\bullet$, a result consistent with the weaker O–H bond in $(t\text{-Bu})_2\text{CNOH}$.

Combining the O–H BDE in acetone oxime calculated at our highest level of theory (84.6 kcal/mol, CBS-APNO, Table 4) with the DFT-calculated BDEs (Table 5) provides an internally consistent, recommended set of BDE values for this group of compounds (see Table 7). Interestingly, the recommended O–H BDEs for $E\text{-}t\text{-Bu}(i\text{-Pr})\text{C}=\text{NOH}$, $(t\text{-Bu})_2\text{C}=\text{NOH}$,

Table 7. Recommended O–H BDEs of Oximes ($\text{RR}'\text{C}=\text{NOH}$)^a

R	R'	BDE ^b	R	R'	BDE ^b
H	H	83.4	9-fluorenyl		81.8
H	Me	84.7/82.6	Et	Et	83.8
H	CF_3	84.4/82.2	<i>i</i> -Pr	<i>i</i> -Pr	82.7
Me	Me	84.6	<i>t</i> -Bu	<i>i</i> -Pr	81.5
H	Ph	83.9/79.4	<i>t</i> -Bu	<i>t</i> -Bu	77.6
Me	Ph	82.8/80.1	<i>t</i> -Bu	1-Ad	77.2/76.9
Ph	Ph	81.6			

^a All values at 298 K in kcal/mol. ^b Values in italics are for the Z -isomer in which the highest priority substituent is cis to the oxime/iminoxyl oxygen.

and E - and $Z\text{-}t\text{-Bu}(1\text{-Ad})\text{C}=\text{NOH}$ are 81.5, 77.6, 77.2, and 76.9 kcal/mol, lower by 1.1, 1.6, 2.0, and 2.3 kcal/mol than the revised calorimetric values of 82.6, 79.2, and 79.2 kcal/mol (Table 1), which were said to be “reliable to within ± 3 kcal/mol”.⁵ The recommended values of the O–H BDE in $t\text{-Bu}(1\text{-Ad})\text{C}=\text{NOH}$ of 77.2 and 76.9 kcal/mol are indistinguishable from the BDEs of 77.0 and 76.5 kcal/mol (Table 5) estimated from the thermolysis of the O -benzyl ether of this oxime in *tert*-butylbenzene. Similarly, the O–H BDEs obtained by the same procedure from the estimated activation enthalpies for the thermolyses of $\text{Ph}_2\text{C}=\text{NOCH}_2\text{Ph}$, $\text{Fl}=\text{NOCH}_2\text{Ph}$, and $(i\text{-Pr})_2\text{C}=\text{NOCH}_2\text{Ph}$, viz., 82.4, 82.0, and 79.7 kcal/mol, respectively, are in fair to excellent agreement with the recommended values, viz., 81.6, 81.8, and 82.7 kcal/mol, respectively.

Summary

The O–H BDEs for oximes that were derived from EC data have been shown to be very badly in error, and the 1973 prediction⁵ that simple unhindered oximes would have O–H BDEs about 5 kcal/mol higher than that of $(t\text{-Bu})_2\text{C}=\text{NOH}$ has been confirmed by a combination of theory and experiment. Thus, after a 12 year hiatus,^{13–15} order has been restored to oxime O–H BDEs. Steacie¹ would have been delighted.

Experimental Section

Determination of α_2^{H} . The α_2^{H} value for di-*tert*-butyl ketoxime was determined by infrared spectroscopy in CCl_4 at 25 °C as previously described.⁵⁶ In brief, at oxime concentrations below 2.3 mM in CCl_4 , the intensities of the free OH fundamental stretching band follow the Beer–Lambert law, indicating that there is no self-association. The intensity of this band was recorded at a single concentration of oxime for several concentrations of two different hydrogen-bond acceptors (HBAs) (acetone and DMSO). The decreasing concentrations of free (non-hydrogen bonded) oxime with increasing concentrations of HBA were calculated from the “free” O–H band intensity using the Beer–Lambert plot. The equilibrium constant, K^i , for 1:1 complex formation between the oxime and HBA was calculated from the least-squares slopes of plots of $[\text{oxime:HBA}]_{\text{H-bonded}}/[\text{oxime}]_{\text{free}}$ against $[\text{HBA}]_{\text{free}}$ to be 20.1 and 22.1 in DMSO and 2.88 and 2.80 in acetone. A mean α_2^{H} value of 0.43 was calculated from these equilibrium constants using eqs 15 and 16:

$$\log K^i = L_{\text{HBA}} \log K_A^{\text{H}} + D_{\text{HBA}} \quad (15)$$

$$\alpha_2^{\text{H}} = (\log K_A^{\text{H}} + 1.1)/4.636 \quad (16)$$

where L_{HBA} and D_{HBA} are known constants because both DMSO and acetone are calibrated HBAs.³³

Thermolyses of O -Benzyl Oxime Ethers. The experimental procedure has been described elsewhere.^{19,39}

(56) See, for example: ref 17b and Astolfi, P.; Greci, L.; Paul, T.; Ingold, K. U. J. Chem. Soc., *Perkin Trans. 2* **2001**, 1631–1633.

Theoretical Calculations. All DFT calculations were done with the medium-level model-2 (MLM2) of DiLabio et al.⁴⁷ unless otherwise indicated. This model involves geometry optimizations and frequency calculations using the (U)B3LYP exchange-correlation functional⁵⁷ and 6-31G(d) basis sets. The frequencies were scaled by 0.9806 as suggested by Scott and Radom.⁵⁸ Single point energies were then calculated with (RO)B3LYP and larger 6-311+G(2d,2p) basis sets. The O–H bond dissociation enthalpies were obtained by calculating the difference between oxime and iminoxyl enthalpies using the standard enthalpic corrections along with the scaled vibrational contributions to the enthalpy. The electronic energy of the hydrogen atom was set to its exact value of -0.5 hartree in these calculations.⁴⁷ For some oxime/iminoxyl radical pairs, CBS-QB3,⁵¹ CBS-APNO,⁵² G3,⁵⁰ and G3MP2⁴⁹ calculations were performed for comparison. All calculations were done with the Gaussian-98 suite of programs⁵⁹ compiled to run on a Silicon Graphics Origin.

Acknowledgment. We thank Dr. Grzegorz Litwinienko for measuring α_2^{H} for di-*tert*-butyl ketoxime and Dr. Philip A. MacFaul for measuring the rate constants for H-atom abstraction by *tert*-butoxyl radicals from three oximes. We also thank Goldstein et al. whose publication⁶⁰ stimulated the addition of

“Order Restored” to our title. D.A.P. thanks NSERC Canada and Vanderbilt University for their support. Dr. Jarrod Smith and the Vanderbilt Center for Structural Biology as well as the Hochschulrechenzentrum Essen are gratefully acknowledged for generous access to their computing resources.

Supporting Information Available: Kinetic data for the thermolyses of some RR'C=NOCH₂Ph in *tert*-butyl benzene and Cartesian coordinates, electronic energies, and thermochemistry of all computed structures in Tables 3–6 as well as Figure 1. This material is available free of charge via the Internet at <http://pubs.acs.org>.

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