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Thermal decomposition of *O*-benzyl ketoximes; role of reverse radical disproportionation

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Thermolyses of seven dialkyl, two alkyl-aryl and two diaryl *O*-benzyl ketoxime ethers, $R^1R^2C{=}NOCH_2Ph$, have been examined in three hydrogen donor solvents: tetralin, 9,10-dihydrophenanthrene, and 9,10-dihydroanthracene. All the oxime ethers gave the products expected from homolytic scission of both the O–C bond (*viz*., $R^1R^2C{=}NOH$ and $PhCH_3$) and N–O bond (*viz.*, $R^1R^2C{=}NH$ and $PhCH_2OH$). The yields of these products depended on which solvent was used and the rates of decomposition of the *O*-benzyl oxime ethers were greater in 9,10-dihydrophenanthrene and 9,10-dihydroanthracene than in tetralin. These results indicated that a reverse radical disproportionation reaction in which a hydrogen atom was transferred from the solvent to the oxime ether, followed by β-scission of the resultant aminoalkyl radical, must be important in the latter two solvents. Benzaldehyde was found to be an additional product from thermolyses conducted in tetralin. This, and other evidence, indicated that another induced decomposition mode involving abstraction of a benzylic hydrogen atom, followed by β-scission of the resulting benzyl radical, became important for some substrates. Participation by minor amounts of enamine tautomers of the oxime ethers was shown to be negligible by comparison of thermolysis data for the *O*-benzyloxime of bicyclo[3.3.1]nonan-9-one, which cannot give an enamine tautomer, with that of the *O*-benzyloxime of cyclohexanone.

Introduction

Interest in the free-radical chemistry of oxime ethers ($R^1C(R^2){=}NOR^3$, **2**) has been steadily rising since discoveries that they act as very efficient radical acceptors in intermolecular addition and cyclization reactions,[1a–i] that their addition rates are enhanced by Lewis acids,[2] and consequently that more efficient preparations of amine derivatives and *N*-heterocycles are thereby possible. Compound types suitable for clean thermal generation of free radicals are quite limited and therefore potential new precursors are of special interest. It was shown recently that direct photolysis of *O*-alkyl aldoxime ethers, using standard organic equipment, was very inefficient and gave product yields too low for preparative purposes.[3] As expected, however, aryl aldoxime ethers ($ArCH{=}NOR^3$) readily added carbon-, tin-, sulfur- and even oxygen-centered radicals ($X^{\bullet}$). The resulting alkoxyaminyl radicals ($ArCH(X)\text{-}N^{\bullet}OR^3$) were observed and characterized by EPR spectroscopy. When R^3 contained α-H-atoms, *t*-butoxyl radicals abstracted these H-atoms in competition with addition to the CH= end of the double bond. Photosensitized dissociation of ketone *O*-(4-cyanophenyl)oximes was, however, found to afford iminyl radicals that proved useful for dihydropyrrole syntheses.[4]

A study of the thermal decomposition of aryl benzyl ethers, $ArOCH_2Ph$, in a good hydrogen donor solvent, found that the O–C bond scission reaction is 'well-behaved' *i.e.* free of induced decomposition.[5] It appeared possible that thermolyses of oxime ethers might proceed in similar fashion. However, scission of their N–O bonds to provide iminyl and alkoxyl radicals, and scission of their O–R bonds to generate iminoxyl and C-centered radicals, were both possible dissociation modes. The dominant scission was expected to depend on the substituents (R^1, R^2 and R^3). Our objective is to examine the thermolytic behaviour of a range of oxime ethers under various experimental conditions and hence to discover the dominant homolysis modes and map out the effect of substituents and solvents on the dissociations. We chose *O*-benzyl oxime ethers in an effort to bias the reaction in favor of O–C bond scission because of the resonance stabilization in the released benzyl radical. Initial research with *O*-benzyl benzophenone oxime ether (**2c**, R^1, R^2 = Ph) indicated that comparatively high temperatures (≥150 °C) were needed to bring about thermal dissociation. Work with oximes ($R^1C(R^2){=}NOH$, **1**) in 1973 had shown[6] that their O–H bond dissociation enthalpies (BDEs) decreased when bulky groups R^1 and R^2 were attached to the iminyl C-atom, because of greater alkyl–alkyl and alkyl–oxygen repulsion in the parent oximes compared to the released iminoxyl radicals. It seemed likely that similar steric factors could be expected for the analogous oxime ethers and therefore our selection of substituents included bulky *t*-butyl and 1-adamantyl groups intended to promote dissociation under milder conditions. In this paper we report our results on the thermal and induced decompositions of aryl- and alkyl-*O*-benzyl oxime ethers at different temperatures in hydrogen donor solvents. H-Donor solvents were found to promote induced dissociation by the reverse radical disproportionation (RRD) process.

Results

Oxime ethers can be prepared by reaction of an oxime and an alkyl bromide in the presence of caesium carbonate in DMF.[7] Alternatively, the appropriate carbonyl compound may be reacted with an *N*-alkoxyphthalimide and hydrazine hydrate.[8] For the preparation of *O*-benzyl oxime ethers we found that addition of the appropriate ketone to a solution of *O*-benzyl hydroxylamine hydrochloride in anhydrous pyridine gave high yields in most cases. The excess pyridine was easily removed by washing with a solution of copper(II) sulfate. The series of oxime ethers shown in Scheme 1 was prepared.

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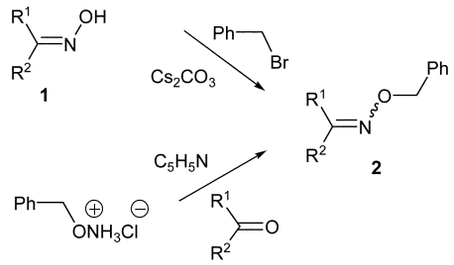


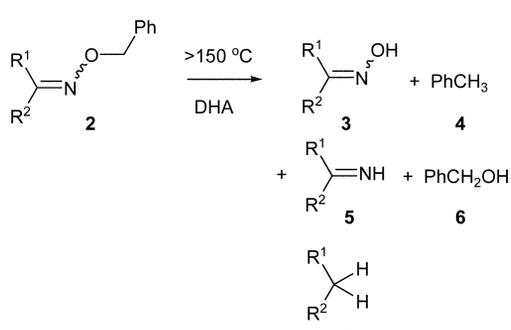
	R^1	R^2
a	Me	Me
b	Me	Ph
c	Ph	Ph
d	1-indanyl	
e	9-fluorenyl	
f	*i*-Pr	*i*-Pr
g	*i*-Pr	*t*-Bu
h	*t*-Bu	*t*-Bu
j	*t*-Bu	1-Ad
k	cyclohexyl	
l	9-bicyclo[3.3.0]nonyl	

Scheme 1 Preparation of *O*-benzyl oxime ethers.

The ^{1}H NMR spectra and GC-MS chromatograms showed that the unsymmetrical compounds (**2b**,**g**,**j**) were formed as mixtures of *syn* (*Z*) and *anti* (*E*) isomers in approximately 1 : 1 ratios if the reactions were conducted at RT.

Thermolysis of *O*-benzyl ketoxime ethers

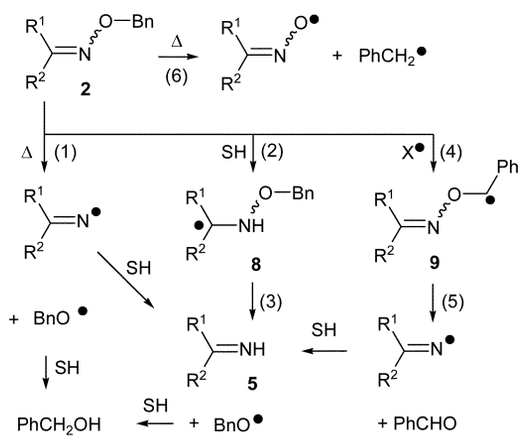
Thermolyses of **2** were carried out in three H-donor solvents: 9,10-dihydroanthracene (DHA), 9,10-dihydrophenanthrene (DHP) and tetralin (TH). Samples were weighed into Pyrex tubes, the solvent was added, the solutions/mixtures were degassed on a vacuum line, flame sealed and then heated for timed intervals. The products were identified by GC-MS and by retention time comparisons with authentic materials and were quantitatively analysed by GC. The main products formed during thermolyses of all the oxime ethers in DHA were the oxime **3**, toluene **4** (approximately equal amounts) together with the imine **5**, and benzyl alcohol **6** also in approximately equal amounts (Scheme 2).



Scheme 2 Products from thermolyses of *O*-benzyl oxime ethers.

Similar products were formed in all the solvents, but the yields of imine and $PhCH_2OH$ decreased as the solvent was changed from DHA to DHP to TH (Table 1). Because the yields of these last two products depended on the solvent in which the thermolyses were carried out they cannot be formed solely *via* direct homolysis of the oxime N–O bond followed by H-atom abstraction from the solvent. For the aromatic ketoxime ethers (R^1 and/or R^2 = aryl) the imine/$PhCH_2OH$ ratios were generally somewhat smaller than 1.0 in DHP and they were even smaller in DHA and, in these last two solvents, the rates of decomposition of all the *O*-benzyl oximes were greater than in TH. Furthermore, in DHA when R^1, R^2 = Ph, Ph; 1-indanyl and 9-fluorenyl, new products appeared, the corresponding aromatic hydrocarbon, $R^1R^2CH_2$, and ketone, $R^1R^2C{=}O$. However, the summed total concentrations of imine, hydrocarbon and ketone remained approximately equal to the benzyl alcohol concentration, *e.g.*, the thermolysis of 9-fluorenyl-*O*-benzyl oxime ether, **2e**, in DHA for 24 h at 423 K gave Fl=NH = 23.2×10^{-4} M, $FlH_2 = 22.0 \times 10^{-4}$ M and Fl=O = 3.9×10^{-4} M, total = 49.1×10^{-4} M, while the yield of $PhCH_2OH$ was 50.5×10^{-4} M (*cf.* Table 1).

The rates of disappearance of the starting oxime ethers and the rates of appearance of the products were determined for most of compounds **2**. The kinetics clearly indicated an active role for DHP and the kinetics and products an even more active role for DHA in the overall chemistry. This role involves a direct hydrogen atom transfer from the solvent (SH) to the oxime ether, a reverse radical disproportionation (RRD, reaction 2),[9] followed by β-scission of the resultant aminoalkyl radical **8**, (reaction 3), to form the same products as those derived from N–O bond homolysis, (reaction 1, Scheme 3).



Scheme 3 Mechanism of thermal decomposition of *O*-benzyl oxime ethers.

The RRD reaction (2) is favored when the aminoalkyl radical which is produced *i.e.* **8** is resonance stabilized (as is the case when R^1 and/or R^2 = aryl) and when the solvent has a relatively low C–H BDE, *i.e.*, especially for DHA. Favourable thermodynamic factors also provide the driving force for the further conversion of arylimines, particularly 9-fluorenylimine *vide supra* into the $R^1R^2CH_2$ hydrocarbon, a process which probably follows the same mechanism as that which has been advanced to explain the reduction of aromatic ketones to hydrocarbons by hydrogen donor solvents at elevated temperatures.[10] In short, the corresponding ketyl radical would form by another RRD reaction with DHA, followed by fluorenol formation and subsequent deoxygenation.

For the oxime ethers, **2**, where R^1 and/or $R^2 \neq$ aryl, the transfer of an H-atom to nitrogen (reaction (2)) by the RRD process does not give a resonance stabilized radical **8**. In these cases the alternative RRD, in which an H-atom is transferred to the C-atom of the C=N bond, needs to be considered. This process would ultimately lead, *via* β-scission of the first formed aminyl radical, to toluene and a secondary nitroso compound that would tautomerize to an oxime. The DFT computed hydrogen affinities (HAs) for N-addition and C-addition to **2a** ($R^1 = R^2$ = Me) (B3LYP6-31G(d,p)//B3LYP6-31G(d,p)) were found to be −25.5 and −38.9 kcal mol^{-1} respectively. Thus, C-addition of an H-atom to **2** is thermodynamically disfavoured but cannot be completely ruled out. It seems likely to be even less important for the other oxime ethers because of increased steric protection of the sp^2 carbon. However, the main thermolysis products, particularly in DHA, were benzyl alcohol **6** and imine **5** (Table 1) which cannot be accounted for by a RRD involving H-atom transfer to carbon. An alternative, acid catalysed hydrolysis of the oxime ethers to the imine and benzyl alcohol is

Table 1 Product yields (mol%)[a] from thermolyses of *O*-benzyl oxime ethers **2** in various solvents at 423 K

Oxime ether	Solvent	Therm. time/h	%Conv.[c]	%**3** (Oxime)	%**4** (PhMe)	%**5**[d] (Imine)	%**6** ($PhCH_2OH$)	% PhCHO
2a	DHA	216	6.2	0.6	0.7	3.1	5.4	0
(Me, Me)	DHP	″	4.6	0.4	0.4	0.3	4.0	0
	TH	″	0.8	0.4	0.4	0.03	0.03	0.6
(*E*)-**2b**	DHA	144	16.1	0.5	0.6	10.8	15.5	0
(Me, Ph)	DHP	192	1.4	0.7	0.7	0.7	0.7	0
	TH	264	0.7	0.1	0.6	0.1	0.1	–[b]
2c	DHA	24	23.7	0.1	0.1	19.7[f]	23.5	0
(Ph, Ph)	DHP	240	2.8	1.1	1.2	1.7	1.6	0
	TH	264	1.3	1.2	1.2	0.1	0.1	0.1
2d	DHA	192	6.9	0.7	0.8	5.5[f]	6.0	0
(Indanyl)	DHP	″	1.6	0.6	0.7	0.8	0.8	0
	TH	″	0.8	0.7	0.7	0.1	0.1	nd[e]
2e	DHA	24	40.6	0.1	0.1	21.7[g]	40.5	0
(Fluorenyl)	DHP	168	3.6	1.2	1.3	2.2	2.3	0
	TH	″	1.0	0.9	0.9	0.1	0.1	0.1
2f	DHA	264	16.1	4.9	0.5	10.7	11.2	0
(*i*-Pr, *i*-Pr)	DHP	″	5.8	5.0	5.0	0.8	0.8	0
	TH	″	6.3	5.8	5.8	0.5	0.5	0.2
2g	DHA	264	20.9	6.6	6.7	13.7	14.1	0
(*i*-Pr, *t*-Bu)	DHP	″	7.9	6.4	6.7	1.1	1.2	0
	TH	″	7.7	7.1	6.9	0.6	0.6	0.7
2h	DHA	264	58.1	41.3	41.4	16.4	16.8	0
(*t*-Bu, *t*-Bu)	DHP	216	32.7	28.9	29.5	3.1	3.2	0
	TH	″	34.8	29.5	31.5	3.2	3.3	5.8
2j	DHA	192	63.2	47.8	48.2	14.5	15.0	0
(*t*-Bu, Ad)	DHP	″	58.5	52.6	53.0	5.5	5.5	0
	TH	″	54.4	49.0	48.9	5.4	5.4	nd
2k	DHA	264	22.4	0.3	0.1	7.1	21.9	0.1
(Cyclohexyl)	DHP	″	19.7	0.0	0.1	17.5	0.7	2.0
	TH	″	3.2	0.0	0.0	1.8	0.2	1.3
2l	DHA	264	55.7	0.1	0.1	52.0	53.8	1.7
(Bicyclononanyl)	DHP	″	3.4	0.1	0.0	3.2	1.0	0.1
	TH	″	2.3	0.0	0.0	1.8	0.3	0.2

[a] Determined by GC. [b] Could not be determined because of an impurity. [c] Mol% **2** reacted; determined from the unreacted **2**. [d] May include $^1R^2RC{=}O$ from hydrolysis of **5** and **2** during work-up/analysis. [e] nd = not determined. [f] Yld. of $^1R^2RCH_2$ = 0.1% [g] Yld. of $^1R^2RCH_2$ = 17.7%.

Table 2 Measured first-order rate constants (s^{-1}) for dissociation of *O*-benzyl oxime ethers **2** in three solvents[a] at 423 K

Oxime ether	R^1, R^2	$10^8 k_{dis}$[b] in TH	$10^8 k_{dis}$ in DHP	$10^8 k_{dis}$ in DHA
2a	Me, Me	0.51	1.3	5.9
(*E*)-2b	Ph, Me	0.70	1.9	28
2c	Ph, Ph	1.5	3.3	272
2d	1-indanyl	1.2	2.0	10
2e	9-fluorenyl	2.2	5.3	705
2f	*i*-Pr, *i*-Pr	6.9	6.5	19
2g	*t*-Bu, *i*-Pr	8.1	8.5	24
2h	*t*-Bu, *t*-Bu	50	46	55
2j	Ad,[c] *t*-Bu	109	107	158
2k	cyclohexyl	2.5	2.7	24.3
2l	bicyclononyl	0.44	1.1	99.3

[a] TH = tetralin; DHP = 9,10-dihydrophenanthrene; DHA = 9,10-dihydroanthracene. [b] Measured overall rate constants obtained from the slopes of plots of ln ($[\mathbf{2}]_{t=t}/[\mathbf{2}]_{t=0}$) *versus* time ($t$) using $[\mathbf{2}]_{t=0} = [\mathbf{2}]_{t=t} + 0.5 \times$ [sum of products]. Good straight lines were obtained in all cases, $R^2 > 0.98$. Estimated error for rate constants is ±10%. [c] 1-Adamantyl.

a possibility since similar ionic processes have been suggested previously in hydrocarbon solvents.[10]

In Table 2, k_{dis} represents the overall (pseudo) first-order rate constant for the disappearance of **2**. Because each sample tube was individually prepared, the initial oxime ether concentrations varied slightly and therefore k_{dis} was calculated using the internal mass balance:

$$[\mathbf{2}]_{t=0} = [\mathbf{2}]_{t=t} + 0.5 \times \Sigma[\text{prods.}]$$

except for the thermolyses in TH where loss of starting material was quantified.

The disappearance of the oxime ethers **2** was slower in TH than in DHP or DHA and furthermore a new product, PhCHO, was observed in this solvent. We attribute the formation of this product to radical abstraction of a benzylic H-atom from **2**, reaction (4), followed by β-scission of the resulting radical **9** to produce benzaldehyde and more iminyl radicals (Scheme 3). The occurrence of similar H-abstractions from oximes with α-H-atoms has been referred to above.[3] The identity of radical X has not been established with certainty but it was probably the solvent-derived tetralinyl radical.

Discussion

Reverse radical disproportionation

The comparatively high conversions and high yields of imine and benzyl alcohol for the diphenyl- (**2c**) and fluorenyl- (**2e**) oxime ethers (Table 1) indicated that the RRD reaction was the major pathway in DHA. Oxime ether **2j** is expected to have a comparatively low O–C BDE, but it is evident that the RRD

process accounts for much decomposition of this compound in the H-donor solvents too.

Consideration of the HD solvent's C–H BDEs[11] explains why reaction 2 is more favoured in DHA (BDE = 75.2 kcal mol^{-1}) than in DHP (84.2 kcal mol^{-1}) and TH (83.6 kcal mol^{-1}). However, this does not explain why more RRD products are formed in DHP than in TH. We suggest that this difference between DHP and TH is a consequence of very different H-atom donor abilities of the two dehydro S$^{\bullet}$ radicals. That is, for S$^{\bullet}$ = DHA$^{\bullet}$, DHP$^{\bullet}$, and TH$^{\bullet}$ the C–H BDE/kcal mol^{-1} are:[11] 42.9, 31.9 and 46.4, respectively. Probably DHA$^{\bullet}$, and TH$^{\bullet}$ are destroyed largely, or entirely, by bimolecular self-disproportionation reactions. However, DHP$^{\bullet}$ with its very weak C–H BDE is such a good H-atom donor that it reacts directly with the oxime, reaction (7).[12] This reaction will be followed by reaction (3), thus forming the same products as in a true RRD reaction.

$$R^1R^2C{=}NOCH_2Ph + DHP^{\bullet} \longrightarrow R^1R^2C^{\bullet}NHOCH_2Ph + \text{phenanthrene} \quad (7)$$

The data in Table 2 for the "clean" RRD reactions involving DHA show that when both R^1 and R^2 are alkyl groups their physical size has a much smaller effect on the rate of reaction (2) than when they are both aryl groups (Ph, Ph and fluorenyl). This is consistent with the known importance of thermodynamic factors in driving endothermic RRD processes.[9,10] In fact, work on the deoxygenation of aromatic ketones in H-donor solvents at elevated temperatures has led to an expression for the rate constant k_{RRD} for this RRD reaction (eqn. 8) which requires only a knowledge of the reaction enthalpy, $\Delta_{RRD}H$ (in kcal mol^{-1}), since $\ln(A_{RRD}) = 13.6 + 0.16\Delta_{RRD}H$.[10]

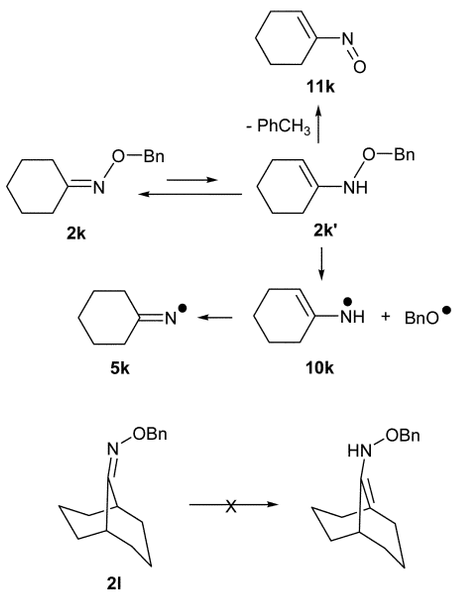
$$k_{RRD} = A_{RRD}\exp[(-\Delta_{RRD}H + 3)/RT] \quad (8)$$

The DFT calculated hydrogen affinities[13] (in kcal mol^{-1}) for R^1R^2 C=NOH are: Ph, Me (−33.0); Ph, Ph (−38.7); 1-indanyl (−31.8); 9-fluorenyl (−39.8) which can be combined with the DFT C–H BDE for DHA to predict that the relative values of k_{RRD}(SH = DHA) for these four oximes at 423 K would be expected to be 1 : 354 : 0.30 : 1099, respectively. However, the experimental relative rates for the corresponding four *O*-benzyl ethers (Table 2, column 5) are: 1 : 10 : 0.35 : 25. Thus, the kinetics of the RRD reactions between DHA and aromatic *O*-benzyl ketoxime-ethers are determined by more than the simple thermodynamics exemplified by eqn. (8).[14]

Tautomerism of the alkyl oxime ethers would produce minor amounts[15] of the enamine tautomers, *e.g.* **2k′** (Scheme 4). Scission of the N–O bonds of these enamines might be much more rapid than for the oximes because the hybridization at the N-atom is sp^3 in the enamines, and because the product radicals, *e.g.* **10k**, are delocalized aza-allyl radicals. The more facile cleavage of the enamine N–O bond is supported by DFT computations (B3LYP6-31G(d,p)//B3LYP6-31G(d,p))[16,17] for **2a** which gave ΔH values of 32.3 and 45.7 kcal mol^{-1} for N–O cleavage of the enamine and oxime tautomers of **2a**, respectively.

Another possibility for the enamine tautomers was direct thermal four-centre elimination of toluene with production of nitroso-compounds such as **11k**. The importance of these processes for dialkyl oxime ethers was probed by synthesis of bicyclo[3.3.1]nonanyl oxime ether **2l**. This is a dialkyl analogue that is incapable of tautomerization because the enamine would contain a bridgehead (anti-Bredt) double bond.

Table 1 shows that similar products were obtained from **2k** and **2l**. None of the nitroso-compound **11k** was detected; neither did the other dialkyl oxime ethers afford nitroso derivatives and hence the four-centre elimination of toluene can be ruled out at the temperatures of our thermolyses. Table 2 shows the rate of consumption of **2k** was significantly faster than **2l** in TH while the reverse was true in DHA. k_{dis} for **2l** was comparable to that of the di-methyl substrate **2a** (also having the potential for enamine formation). The yield of PhCHO from **2k** in TH was appreciably higher than from **2l** (Table 1). This probably indicates that the abstraction reaction (4), was more important for **2k** than for **2l** which may be explained by the slightly greater steric shielding of the CH_2 group in **2l**. Thus, the greater value of k_{dis} for **2k** than **2l** in TH can probably be attributed to reaction (4) rather than to the participation of enamine tautomers.



Scheme 4 Enamine tautomers of *O*-benzyl oxime ethers.

Tables 1 and 2 show that the sterically crowded oximes **2h** and **2j** dissociated appreciably more rapidly than the other oximes in TH. Thus, in the solvent where RRD is least important, and direct O–C scission (reaction 6) dominates, bulky *t*-Bu and 1-Ad groups attached to the iminyl C-atom, appeared to weaken the O–C bond; probably because of alkyl–alkyl and alkyl–oxygen repulsion in the parent oxime ethers. It is probable that the O–C BDEs of all the *O*-benzyl ketoximes studied are rather similar because their rates of thermal decomposition in TH could be monitored at the same temperature (423 K, see Tables 1 and 2). As judged by k_{dis} values in TH, where the RRD process is comparatively minor (Table 2), the O–C BDEs for *O*-benzyl oxime ethers are expected to decrease in the order:

2l(bicyclo) ~ **2a**(Me_2) > **2b**(Me,Ph) > **2c**(Ph_2) ~ **2d**(ind) > **2e**(fluor) ~ **2k**(cyclohexyl) > **2f**(*i*-Pr_2) ~ **2g**(*t*-Bu,*i*-Pr) > **2h**(*t*-Bu_2) > **2j**(*t*-Bu,Ad)

Experimental

All reactions were conducted under N_2 atmosphere. All NMR spectra (^1H, ^{13}C) were recorded on an AC-Bruker instrument (400 MHz). Unless otherwise noted, proton and carbon chemical shifts are reported in ppm using residual $CHCl_3$ as an internal standard at 7.26 and 77.0 ppm respectively. Analysis by electrospray mass spectrometry was performed on a VG Quattro 1 (Micromass) mass spectrometer equipped with a pneumatically-assisted electrospray ionization source, operating in positive mode. HRMS analysis was performed on a JEOL JMS-AX505H mass spectrometer. GC-MS samples were run on a HP 5890 Gas Chromatograph with a 5970 Series Mass Selective Detector.

Materials

The nine oximes, $R^1R^2C{=}NOH$, required as GC standards were synthesized by reactions of the corresponding ketones with

hydroxylamine hydrochloride under standard (basic) conditions. The three ketoximes for which the ketones were not available commercially *viz.*, $Me_3C(Me_2CH)C{=}O$, $(Me_3C)_2C{=}O$ and $Me_3C(1\text{-Ad})C{=}O$, were prepared by syringe addition (~1 cm^3 min^{-1}) of *t*-butyllithium (30 cm^3 of 1.7 M, 0.051 mol) to 0.050 mol of the alkyl nitrile under nitrogen according to the literature method.[6,18,19] The mixture was stirred until the reaction was complete (TLC, 1–3 h) and then ethanol (5 cm^3) was added, followed by acetic acid (3 cm^3). Ethanol (65 cm^3) and *O*-benzylhydroxylamine hydrochloride (8.0 g) were added and the solution was refluxed for 5–8 h. Purification was by column chromatography (hexane/ethyl acetate, 3 : 1) and final yields of these hindered *O*-benzyloxime ethers were *ca.* 80%.

General procedure: ethanone, 1-phenyl-, *O*-(phenylmethyl)oxime, 2b

O-Benzylhydroxylamine hydrochloride (3.19 g, 0.02 mol) was suspended in anhydrous pyridine (40 cm^3) at room temperature (~80% dissolved), and acetophenone (2.33 cm^3, 0.02 mol) was added to the suspension in one portion *via* syringe. The solution turned clear immediately after the addition. The solution was stirred at room temperature overnight, and the progress of the reaction was monitored by TLC (hexane : ethyl acetate = 5 : 1) and GC-MS. Upon completion, the reaction mixture was poured into distilled water (50 cm^3), extracted with EtOAc (2 × 50 cm^3), and the combined organic phases were washed several times with saturated, aqueous $CuSO_4$ solution to remove any traces of pyridine. It was then dried ($MgSO_4$) and concentrated on a rotavap and purified by column chromatography (hexane : ethyl acetate = 5 : 1) to give **2b** as a colorless liquid (3.90 g, 87%). Note that if the reaction was conducted at room temperature, then both isomers of **2b** could be observed by GC-MS and ^{1}H NMR; but if the reaction was refluxed for 6 h, only one isomer was obtained. In the case of benzophenone, refluxing for 8 h was required for the reaction instead of room temperature.

Ethanone, 1-phenyl-, *O*-(phenylmethyl)oxime 2b[20,21]

Clear liquid, δ_H 2.30 (s, 3H). 5.27 (s, 2H), 7.33–7.46 (m, 8H), 7.66–7.68 (m, 2H); δ_C 13.0, 76.3, 126.2, 128.2, 128.3, 128.4, 128.7, 129.2, 136.7, 138.3, 155.1; second isomer δ_H 2.22 (s, 3H), 5.13 (s, 2H), ArH overlapped by 1st. isomer; δ_C 21.9, 76.0, 126.3, 127.7, 127.9, 128.1, 128.5, 129.1, 134.7, 138.5, 154.3; *m*/*z* (electrospray) 226.1. $C_{15}H_{16}NO$ requires 226.1.

2-Propanone, *O*-(phenylmethyl)oxime 2a[20,22]

Clear liquid, δ_H 1.90 (s, 3H), 1.92 (s, 3H), 5.10 (s, 2H), 7.30–7.38 (m, 5H); δ_C 16.2, 22.3, 75.6, 128.0, 128.3, 128.7, 138.7, 155.6; *m*/*z* (electrospray) 164.0. $C_{10}H_{14}NO$ requires 164.1.

Methanone, diphenyl-, *O*-(phenylmethyl)oxime 2c[23]

White solid, mp 54–55 °C; δ_H 5.26 (s, 2H), 7.3–7.49 (m, 15H); δ_C 76.9, 127.9, 128.3, 128.5, 128.6, 128.7, 129.2, 129.7, 133.8, 136.9, 138.6, 157.5; *m*/*z* (CI) 288.1347. $C_{20}H_{18}NO$ requires 288.1310.

Indan-1-one, *O*-(phenylmethyl)oxime 2d

δ_H 2.96–3.11 (m, 4H), 5.29 (s, 2H), 7.26–7.53 (m, 8H), 7.79 (d, J = 7 Hz, 1H); δ_C 26.9, 28.8, 76.4, 121.9, 125.7, 127.9, 128.0, 128.2, 128.5, 130.5, 136.2, 138.4, 148.6, 163.5; *m*/*z* (%), 237 (27, M^+), 220 (3), 207 (5), 146 (2), 130 (4), 115 (11), 103 (5), 91 (100), 77 (11), 65 (9), 51 (8).

Fluoren-9-one, *O*-(phenylmethyl)oxime 2e

White solid, mp 59 °C, δ_H 5.55 (s, 2H), 7.30–7.58 (m, 9H), 7.63–7.70 (m, 2H), 7.84 (d, J = 7 Hz, 1H), 8.34, (*d*, J = 7 Hz, 1H); δ_C 120.0, 120.1, 121.9, 128.0, 128.2, 128.3, 128.4, 128.7, 129.6, 130.0, 130.8, 131.1, 135.8, 137.7, 140.4, 141.6, 152.7; *m*/*z* (%) 285 (29, M^+), 255 (19), 177 (6) 163 (11), 151 (7), 106 (1), 91 (100), 77 (6), 65 (7), 51 (4).

Pentan-3-one, 2,4-dimethyl oxime

δ_H 1.14 (d, J = 7 Hz, 6H), 1.18 (d, J = 7 Hz, 6H), 2.54–2.61 (m, 1H), 3.18–3.25 (m, 1H), 8.86 (br, s, 1H); δ_C 19.2, 21.7, 27.9, 31.1, 169.2; *m*/*z* (CI) 130.1.

Pentan-3-one, 2,4-dimethyl-, *O*-(phenylmethyl)oxime 2f

Clear liquid, δ_H 1.12 (d, J = 7 Hz, 6H), 1.15 (d, J = 7 Hz, 6H), 2.53–2.56 (m, 1H), 3.05–3.09 (m, 1H), 5.07 (s, 2H), 7.30–7.39 (m, 5H); δ_C 19.4, 21.6, 28.6, 31.7, 75.8, 127.8, 128.3, 128.6, 139.0, 169.2; *m*/*z* (%) 219 (18, M^+), 202 (6), 177 (3), 128 (2). 91 (100), 77 (10), 65 (9); *m*/*z* (CI) 220.1692. $C_{14}H_{22}NO$ requires 220.1701.

Pentan-3-one, 2,2,4-trimethyl-, *O*-(phenylmethyl)oxime 2g (mixture of 2 isomers, 3 : 2 ratio)

Clear liquid, δ_H 1.13–1.27 (m, 15H), 2.53–2.68 (m, 1H), 5.03 and 5.05 (s, s, 2H), 7.30–7.40 (m, 5H); δ_C 19.3, 22.9, 27.9, 28.7, 29.9, 31.4, 38.4, 76.0, 76.1, 127.7, 128.4, 128.5, 128.5, 139.0, 169.4; *m*/*z* (%) (EI) 233 (3, M^+), 216 (2), 191 (2), 174 (1), 142 (1), 115 (1), 105 (1), 91 (100), 77 (10), 65 (8), 57 (17), 51 (7); *m*/*z* (CI) 234.1823. $C_{15}H_{24}NO$ requires 234.1858.

Pentan-3-one, 2,2,4,4-tetramethyl-, *O*-(phenylmethyl)oxime 2h[24]

Clear liquid, δ_H 1.27 (s, 9H), 1.39 (s, 9H), 5.10 (s, 2H), 7.3–7.6 (m, 5H); δ_C 29.9, 30.3, 38.7, 40.0, 75.9, 127.5, 128.3, 128.7, 138.8, 168.3; *m*/*z* (CI) 248.1945. $C_{16}H_{26}NO$ requires 248.2014.

Adamantan-1-yl-2,2-dimethylpropan-1-one *O*-(phenylmethyl)-oxime 2j

White solid, mp 65–83 °C, δ_H 1.37 (s, 9H), 1.68 (bs, 6H), 2.02 (bs, 9H), 5.08 (s, 2H), 7.25–7.45 (m, 5H); δ_C 29.1, 30.2, 37.0, 40.5, 46.2, 48.9, 75.8, 128.0, 128.2, 128.3, =C and one quat-C not obs.; *m*/*z* (%) 325 (M^+, 5), 283 (12), 234 (10), 177 (30), 135 (100), 107 (10), 93 (15), 91 (70), 79 (23), 77 (20), 57 (18); *m*/*z* (CI) 326.2574. $C_{22}H_{32}NO$, requires 326.2583.

Cyclohexanone, *O*-(phenylmethyl)oxime 2k[20]

Clear liquid, δ_H 1.58–1.70 (m, 6H), 2.23 (m, 2H), 2.53 (m, 2H), 5.09 (s, 2H), 7.30–7.40 (m, 5H); δ_C 25.7, 25.9, 26.0, 27.2, 32.4, 75.3, 127.7, 128.0, 128.5, 138.5, 161.0; *m*/*z* (CI) 204.1344. $C_{13}H_{18}NO$ requires 204.1310.

Bicyclo[3.3.1]nonan-9-one oxime 1l

Hydroxylamine hydrochloride (50.3 mg, 0.724 mmol) was dissolved in anhydrous pyridine (4 cm^3) at room temperature, and bicyclo[3.3.1]nonan-9-one (100 mg, 0.724 mmol) was added to the stirred solution in one portion. The solution was stirred at room temperature overnight, and the progress of the reaction was monitored by TLC (hexane : ethyl acetate = 4 : 1) and GC-MS. Upon completion, the reaction mixture was worked up as described for **2b** and recrystallization from hexane at −20 °C afforded the oxime (95 mg, 86%) as white crystals: δ_H 1.52–1.60 (m, 2H), 1.84–1.94 (m, 8H), 1.95–2.11 (m, 2H), 2.51 (m, 1H), 3.54 (m, 1H), 7.52–7.60 (bs, 1H); δ_C 21.4, 28.8, 32.1, 33.5, 36.3, 167.9; *m*/*z* (electrospray) 154.1. $C_9H_{16}NO$ requires 154.2.

Bicyclo[3.3.1]nonan-9-one, *O*-(phenylmethyl)oxime 2l

White solid, mp 48–49 °C; δ_H 1.50–1.60 (m, 2H), 1.80–1.91 (m, 8H), 1.92–2.09 (m, 2H), 2.51 (m, 1H), 3.53 (m, 1H), 5.10 (s, 2H), 7.30–7.40 (m, 5H); δ_C 21.3, 30.0, 32.3, 33.7, 36.2, 75.1, 127.6, 127.9, 128.4, 138.8, 168.2; *m*/*z* (CI) 244.1797. $C_{16}H_{22}NO$ requires 244.1788.

Thermolysis of *O*-benzyl oxime ethers

The extent of decomposition of each of the oxime ethers was measured after four or five different periods of time at 423 K in three hydrogen donor solvents (used as received), tetralin (TH), 9,10-dihydrophenanthrene (DHP) and 9,10-dihydroanthracene (DHA). The oxime ether (20–30 μmol) was added to a clean Pyrex ampoule (*ca*. 2 cm^3) to which was then added the hydrogen donor solvent and sealed under vacuum after three or more freeze (TH) or cool to room temperature (DHP and DHA)–pump–thaw (TH) or heat (DHP and DHA) cycles. These ampoules were placed in a temperature controlled GC oven. Ampoules were removed at known times, cooled to room temperature, opened and their contents dissolved in acetone (5 cm^3) containing 0.25 mmol anisole as standard. Products were identified by GC/MS (at 70 eV) and quantified by GC/FID (average of three injections).

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14 The relative rates of dehalogenation of the tautomers of 2-, and 4-substituted phenols (enones) and anilines (imines) by RRD are well reproduced using eqn. (8), but the predicted absolute rate constants are about a factor of 10^5 lower than the experimental values, see: P. Mulder, I. W. C. E. Arends, D. Santoro and H.-G. Korth, *J. Org. Chem.*, 2003, **68**, 4247. Similarly in the present work, eqn. (8) predicts a k_{RRD} of 5.8×10^{-10} s^{-1} for the 9-fluorenyl compound with [DHA] = 4.9 M, whereas the experimental value is 7.0×10^{-6} s^{-1} (see Table 2). Eqn. (8) was derived for the hydrogenation of aromatic ketones *via* the reaction sequence: RRD, cage escape of the geminate radical pair, and eventual H-atom abstraction from the HD solvent. For the *O*-benzyl oxime ethers (and for the halogenated enones and imines) the second step may well be an extremely fast β-scission, *i.e.*, reaction (3), which is able to compete with the thermodynamically favored "back" RRD process, reaction (−2), and cage escape because of the very weak N–O bond in $R^1R^2C^{\bullet}NHOCH_2Ph$. That is, a change in mechanism between the RRD reaction of aromatic ketones and aromatic *O*-benzyl oxime ethers makes eqn. (8) an inappropriate descriptor for the latter class of compounds. However, because of the stronger N–O bond in $R^1R^2C^{\bullet}NHOH$ eqn. (8) may apply to the RRD reactions of aromatic oximes and it predicts that RRD will be below the level of detection which is consistent with observations made in the present work. Eqn. (8) also appears to apply to RRD reactions involving aromatic imines (unpublished results).

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