Synthesis, structural studies and desilylation reactions of some N-2-(trimethylsilyl)ethyl-N-nitrosocarbamates

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Abstract — The present report describes the preparation and characterization of several N-2-(trimethylsilyl)ethyl-N-nitrosocarbamates, designed as precursors to thermally unstable secondary N-nitrosocarbamate anions via fluoride-assisted cleavage. X-ray structural studies demonstrate that the core N-nitrosocarbamate moiety has a nearly planar geometry, with an s'-E orientation at the N–N bond. DFT calculations (B3LYP/6-31C(d)) reproduce accurately the structural features of the title compounds and detailed conformational analysis at the same level of theory addresses the long-standing issue of preferred geometries for three classes of related structures: N-nitrosocarbamates, N-nitrosoureas and N-nitrosoamides. Desilylation studies demonstrate that both the solvent and the fluoride concentration influence the rate of the process.

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1. Introduction

The work reported in this article is a reflection of our continuing efforts to generate and study secondary N-nitrosocarbamates, a class of thermally unstable and chemically labile structures.1 The only known example of a secondary N-nitrosocarbamate, N-nitrosourethane, was prepared more than a 100 years ago from urethane, in a sequence of nitration followed by partial reduction, and conversion to the silver salt.2 Its chemistry was recently revisited, the authors using primarily the organic-soluble tetrabutylammonium salt (Scheme 1).3

The experimental studies and gas-phase calculations led to the conclusion that the N-nitrosourethane anion is a typical ambident nucleophile, yielding products of both N-alkylation and O-alkylation, and the ratio of N- to O-alkylated product depends, as expected, on the steric demand of the alkyl halide. Smaller and less branched alkyl groups lead primarily to N-alkylation, while the O-alkylated product becomes predominant with the use of more sterically hindered substrates. In addition, the theoretical analysis and kinetic measurements demonstrated that the N-nitrosourethane anion and its O-alkylated derivatives undergo thermal decomposition in a concerted fashion, through a four-membered cyclic TS.

Certain questions, however, were not addressed, such as the potential influence of the size of the carbamate alkyl (or aryl) group on the thermal stability of the resultant N-nitrosocarbamate anions and their O-alkylated derivatives. In addition, varying the size of the carbamate alkyl (aryl) group would be expected to influence the regioselectivity in their alkylation reactions. Hence, our goal has

Scheme 1.

Keywords: N-Nitrosocarbamates; X-ray structures; 2-(Trimethylsilyl)ethyl group; Desilylation; DFT calculations.

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been to prepare and study other secondary N-nitrosocarba-
mates, with varying size of the carbamate alkyl (aryl) group,
in an attempt to prepare exceptionally stable structures,
suitable for isolation and solid-state studies. The initial
efforts were focused on adaptation of the synthetic strategy
used in the preparation of N-nitrosourethane salts. Such
attempts have proved futile, prompting us to design and
implement a new methodology, based on the fluoride-
assisted cleavage of a 2-(trimethylsilyl)ethyl group (TMSE)
incorporated into thermally and chemically stable
N-2-(trimethylsilyl)ethyl-N-nitrosocarbamates. The TMSE
group has been used in the past as a protecting group for
alcohols and carboxylic acids, thiols and phosphates. In
a recent article, Bottaro et al. described its use as a
removable moiety at a nitrogen center, in the generation of
the dinitroamide anion.

The present report outlines the details of our synthetic work
leading to the preparation of four N-2-(trimethylsilyl)ethyl-
N-nitrosocarbanates (1a–d, Fig. 1) and the current results
from desilylation experiments. This article also reports the
first crystal structures of N-nitrosocarbanates, compounds
1c and 1d, and compares those with results from gas-phase
DFT calculations (B3LYP/6-31+G(d)).

2. Results and discussion

2.1. Synthesis

The preparation of carbanates 1a–d is outlined in Scheme 2.
The corresponding alcohol (for compounds 1a–c) or 2,4,6-
tris(t-butyl)phenol (for compound 1d) is converted to an
N-2-(trimethylsilyl)ethylcarbamate (2a–d), by means of one
of two general methods (A and B). Method A utilizes a
Hoffmann-type rearrangement reaction of 3-(trimethyl-
silyl)propanamide (4) with the corresponding alcohol, in
the presence of NBS and Hg(OAc)₂. The reaction works
very well for preparation of the ethyl carbamate (2a), but the
yields drop significantly for the t-butyl (2b) and 1-adamantyl
(2c) carbamates, and no reaction is observed in an attempt to
generate the 2,4,6-tris(t-butyl)phenyl carbamate (2d). The
latter was prepared using an alternative approach (Method
B) that includes deprotonation of the starting phenol
followed by reaction with triphosgene, leading to the
generation of 2,4,6-tris(t-butyl)phenyl chlorocarbamate.10
Reaction of the chlorocarbamate with 2-(trimethylsilyl)-
ethanamine (5) affords the carbamate 2d. Compound 5
was prepared according to a patented procedure utilizing
2-(trimethylsilyl)ethanol, which is converted, in a
Mitsunobu reaction, to N-2-(trimethylsilyl)ethylphthali-
mide. The phthalimide, upon reaction with hydrazine
Nitrosation reactions were carried out utilizing three different approaches. Nitrosation in a two-phase (water–ether) system was carried out, with the nitrosating agent generated in the aqueous layer, upon reaction of NaNO₂ with HNO₃. The method gives satisfactory results for carbamates 2a–b, but the yield is significantly reduced in the case of 2c, whereas only traces of nitrosated product are observed in the reaction of 2d. Better yields for carbamates 2a–c (but not 2d) were observed when the nitrosation was performed in anhydrous conditions, with NOBF₄ as a nitrosating agent and the presence of pyridine base. The difficulties in nitrosation of 2d have to be attributed to the steric effect (hindrance) of the two ortho-positioned tert-butyl groups of the aromatic ring. Successful nitrosation of 2d was eventually achieved following a modified version of the method of Overberger and Anselm, which employs NaNO₂ in a mixture of acetic acid and acetic anhydride.

2.2. Structural studies

X-ray crystallographic analysis was conducted on compounds 1c and 1d, providing the first reported crystal structures of N-nitrosocarbamates (Figs. 2 and 3). The asymmetric unit in the unit cell of 1d contains two unique molecules and the only major difference between them is the value of one of the dihedral angles in the TMSE group. Experimental and theoretical data on selected bond lengths, angles and torsional angles are shown in Table 1, together with structural parameters for N-methyl-N-nitroso-p-nitrobenzamidine (MNNB) and N-methyl-N-nitrosoureia (MNU). Bond lengths in 1c and 1d are more comparable to those in the N-nitrosouamide MNNB, particularly the N==O and C==O bonds. The deviations are slightly greater between 1c-d and MNU. The C==O bond is longer in MNU, while the N–N bond is ~0.04 Å shorter.

The N-nitrosocarbamate sub-structure in 1c and 1d, O–C(==O)–N–N==O, is very nearly planar, with a slightly greater twist around the C(1)–N(1) bond in the case of 1c. The overall distortion from planarity is larger than the observed in MNU, but less than that of the N-nitrosouamide MNNB, particularly the N(2)–N(1)–C(1)–O(1) dihedral angle. The 2-(trimethylsilyl)ethyl group in both 1c and 1d adopts an anti conformation. The values for the dihedral angle C(4)–Si–C(3)–C(2) demonstrate that in the case of 1c and one of the unique molecules in the unit cell of 1d there is a nearly ideal gauche positioning of the C(2)H₃ group relative to the methyl groups at the silicon center. The second unique structure for 1d exhibits an almost 18° deviation from the gauche-orientation.

As evident from Table 1, the theoretically derived structural data are in very close agreement with the experimental parameters. The reported results are from gas-phase DFT studies at the B3LYP/6-31+G(d) level of theory. All optimized minima structures, except for those of carbamate 1d, were further validated by frequency calculations at the same level of theory and they had sets of only positive second derivatives. Values of Gibbs free energy differences were obtained after frequency calculations. The computed values for bond lengths are usually within ±0.01 Å of the experimental ones and the differences between theoretical and experimental values for angles and dihedral angles are usually within ±3°. In general, DFT tends to slightly exaggerate the planarity of the core structures for both the carbamates 1c–d and MNU. The global minimum structures for the four N-nitrosocarbamates 1a–d are shown in Figure 4.
Table 1. Selected experimental (bold characters) and theoretical bond lengths (Å) and angles (°) for N-nitrosocarbamates 1a–1d, N-methyl-N-nitroso-p-nitrobezamide (MNNB) and N-methyl-N-nitrosourea (MNU)

<table>
<thead>
<tr>
<th>Bond lengths and angles</th>
<th>1a</th>
<th>1b</th>
<th>1c</th>
<th>1d</th>
<th>MNNB</th>
<th>MNU</th>
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<td>O(1)–C(1)</td>
<td></td>
<td></td>
<td>1.200(4)</td>
<td>1.203(5), 1.197(5)</td>
<td>1.204(5)</td>
<td>1.215(2)</td>
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<td>N(1)–N(2)</td>
<td></td>
<td></td>
<td>1.217</td>
<td>1.210</td>
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<td>N(1)–C(1)–N(2)</td>
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<td></td>
<td>1.369</td>
<td>1.366</td>
<td>1.370</td>
<td>1.369</td>
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<tr>
<td>O(3)–N(2)–O(2)</td>
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<td>1.418</td>
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<td>1.413</td>
<td>1.416</td>
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<tr>
<td>O(2)–C(1)</td>
<td>1.218</td>
<td>1.220</td>
<td>1.220</td>
<td>1.218</td>
<td>1.216</td>
<td>1.220</td>
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<td>N(2)–N(1)–C(1)</td>
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<td></td>
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<td>1.328</td>
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<td>1.345</td>
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<td>Si–C(3)</td>
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<td></td>
<td>1.880(3)</td>
<td>1.872(5), 1.886(4)</td>
<td>1.880(3)</td>
<td>1.872(5), 1.886(4)</td>
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<tr>
<td>O(3)–N(2)–N(1)</td>
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<td></td>
<td>113.2(2)</td>
<td>112.6(4), 113.0(4)</td>
<td>113.8(4)</td>
<td>114.4(2)</td>
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<td>C(1)–N(1)–N(2)–O(3)</td>
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<td>N(2)–N(1)–C(1)–O(1)</td>
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<tr>
<td>C(4)–Si–C(3)–C(2)</td>
<td>178.4</td>
<td>178.1</td>
<td>178.5</td>
<td>179.2</td>
<td>162.5</td>
<td>180.0</td>
</tr>
</tbody>
</table>

Theoretical data from global minimum structures optimized at the B3LYP/6-31 + G(d) level.

*a* Atom labels in accordance with the crystallographic designation for compounds 1e–d.

*b* X-ray data given for each of the two unique molecules in the asymmetric unit of 1d.

*c* X-ray data from Ref. 15.

2.3. Conformational analysis

Calculations demonstrate that each of the compounds 1a–d has a set of rotamers with respect to both the C(1)–N(1) bond (s-trans and s-cis) and the N(1)–N(2) bond (s-E and s-Z). Table 2 lists the relative Gibbs free energies and the Boltzmann statistical contributions for the rotamers of structures 1a–c, MNU and MNNB. In each case the corresponding (s-E, s-trans) isomer is the global minimum, and in the cases of 1c, 1d, MNU and MNNB these are in agreement with the X-ray crystal structures. Nakayama and Kikuchi reached similar conclusions in their recent theoretical studies of several N-nitroso compounds. In almost all of the studied cases the (s-E, s-cis) isomer is the lowest energy local minimum. One exception is MNU, in whose case the lowest energy local minimum is the (s-Z, s-trans) structure. The latter is most likely due to stabilizing hydrogen bonding realized between the NH_2 and NO groups in MNU, which has been suggested earlier based on NMR and IR studies. In the cases of MNNB and MNU calculations could not locate a minimum structure corresponding to the (s-Z, s-cis) isomer, which appears to be due to steric repulsion.

The currently available experimental and theoretical data provide valuable information towards resolving the issue of thermal stability of N-nitroso compounds, which in turn bears relation to the relative stability of the s-E and s-Z conformations. In the s-Z conformation there is spatial proximity of the nitroso group oxygen center to the carbonyl...
carbon, and an intramolecular reaction becomes possible, leading to decomposition (Scheme 3).\textsuperscript{21,22} No such reaction is feasible starting with the \textit{s}-\textit{E} isomer. Thus, it seems that greater relative stability of the \textit{s}-\textit{E} isomer is a pre-requisite for thermal stability of the corresponding \textit{N}-nitroso compound.

\begin{center}
\begin{tabular}{lcccc}
\textbf{Table 2. Relative Gibbs free energies of conformers of \textit{N}-2-(trimethylsilyl)ethyl-\textit{N}-nitrosocarbamates 1a-1c, \textit{N}-methyl-\textit{N}-nitroso-\textit{p}-nitrobezamide (MNNB) and \textit{N}-methyl-\textit{N}-nitrosourethane (MNU), with respect to rotation around the \textit{N}(1)–\textit{N}(2) bond (\textit{s}-\textit{E} and \textit{s}-\textit{Z}) and the C(1)–\textit{N}(1) bond (\textit{s}-\textit{cis} and \textit{s}-\textit{trans})}\textsuperscript{7} & \\
\textbf{ } & \textbf{1a} & \textbf{1b} & \textbf{1c} & \textbf{MNNB} & \textbf{MNU} \\
\textbf{\textit{s}-\textit{E}, \textit{s}-\textit{trans}} & 0.0 (89.9) & 0.0 (99.5) & 0.0 (97.2) & 0.0 (100) & 0.0 (99.9) \\
\textbf{\textit{s}-\textit{E}, \textit{s}-\textit{cis}} & +1.3 (10.1) & +3.2 (0.5) & +2.1 (2.8) & +6.0 (\sim 0) & +9.2 (\sim 0) \\
\textbf{\textit{s}-\textit{Z}, \textit{s}-\textit{trans}} & +5.5 (\sim 0) & +6.2 (\sim 0) & +5.8 (\sim 0) & +6.3 (\sim 0) & +3.9 (0.1) \\
\textbf{\textit{s}-\textit{Z}, \textit{s}-\textit{cis}} & +6.7 (\sim 0) & +7.7 (\sim 0) & +6.0 (\sim 0) & b & b \\
\end{tabular}
\end{center}

Data from B3LYP/6-31 + G(d) geometry optimizations and frequency calculations. Boltzmann contributions (%) at 298 K given in parentheses.

\textsuperscript{a} Atom labels in accordance with the crystallographic designation for compound 1e.

\textsuperscript{b} Minimum structure was not located.

Secondary \textit{N}-nitrosocarbamate anions are also characterized by resonance stabilization and charge delocalization.\textsuperscript{1} It has been estimated, for example, that \textit{N}-nitrosourethane is more acidic than acetic acid.\textsuperscript{24} Hence, cleavage of the TMSE group, according to Scheme 4, would be expected to occur readily. One significant obstacle arises from the fact that structures 3a-\textit{d} have been demonstrated (in the case of 3a)\textsuperscript{1} or are anticipated to be thermally unstable, thus making it a challenge to find the appropriate conditions for desilylation that would be sufficiently mild not to trigger further decomposition of 3a-\textit{d} to the corresponding alkoxide (phenoxy) anion 6a-\textit{d}.

Our current results are based on studies conducted in DMF or acetonitrile as solvents, with Bu\textsubscript{4}NF-3H\textsubscript{2}O as a fluoride source. Experiments were performed using compounds 1a, with available independent literature data for comparison,\textsuperscript{1} and 1d, whose desilylation was particularly easy to follow by NMR, giving distinct peaks in the aromatic region. All experiments were performed on an NMR scale, in deuterated solvents, so that the progress of reaction and product composition could be monitored directly. Results from the desilylation experiments are shown in Table 3.

(a) Role of the solvent and temperature. The studied reactions showed clear dependence on the nature of the solvent, with the rates being consistently higher in DMF. Thus, in the case of 1a desilylation is complete in 0.5 h even at −15 °C, while in acetonitrile complete desilylation of 1a requires 16 h even at +10 °C. The desilylation reaction is slower in the case of 1d, and the solvent has an even more pronounced effect. Compound 1d is practically stable in acetonitrile at +10°C and only traces of decomposition products were detected after 24 h and 5-fold excess of Bu\textsubscript{4}NF.

(b) Amount of Bu\textsubscript{4}NF-3H\textsubscript{2}O. As Table 3 indicates, the

Scheme 4.
process required some excess of the tetrabutylammonium salt in order to be conducted to completion. In the case of 1a and 1 equiv of Bu4NF·3H2O, the reaction mixture after 24 h at 5 °C showed 14% of unreacted carbamate and the desilylation of 1d with 3 equiv Bu4NF·3H2O at +10 °C was not complete even after 48 h. Typical runs were conducted with 3 to 5-fold excess of Bu4NF·3H2O. We anticipate that the relative amounts of fluoride and rates of desilylation are influenced by the fact that the used fluoride source is a trihydrate. It has been shown, both spectroscopically and theoretically, that the fluoride anion forms hydrate clusters with varying number of water molecules.25–27 This is certain to affect the anion’s reactivity and decelerate the desilylation process.

(c) Product composition. The immediate product of desilylation in each case is the corresponding N-nitroso-carbamate anion 3. However, in most runs, particularly of carbamate 1a, anion 6 was observed as well, in varying quantities. In the case of 1a the product structures, 3a and 6a, were validated by comparison with the available in literature spectral data in acetonitrile solvent.1 In DMF, the NMR pattern of the product mixtures is similar, and we have assigned the quartet at δ 4.14 and the triplet at δ 1.23 to the anion 3a, while the quartet at δ 3.50 and triplet at δ 1.06 were assigned to 6a, after comparison with the spectrum of an independently prepared sample of 6a–NMe4 in DMF-d7. The maximum amount of 3a in the studied cases, determined by integration of NMR signals, was about 40%, but in most runs it was lower and not significantly affected by temperature or the nature of the solvent. The desilylation of 1d on the other hand occurs with predominance and in some cases exclusive formation of the desired product 3d, whose signal for the aromatic H-atoms appears at δ 7.34 ppm in deuterated DMF (Fig. 5a–d).

As Figure 5e demonstrates, subjection of 3d to elevated temperature leads to its decomposition. The product of decomposition has a signal for the aromatic protons at δ 6.86 ppm, and was identified as the aryloxide anion 6d. For comparison, we prepared the lithium salt of 2,4,6-tris(t-butylyphenol), whose signal in the aromatic region is at δ 7.20 ppm (Fig. 5f).

The high percentage of ethoxide 6a in the product mixtures from desilylation of 1a cannot be entirely accounted for by a process of secondary decomposition of the anion 3a, particularly at temperatures below 0 °C, since it would correspond to a much lower thermal stability of 3a than established in earlier studies. An alternative explanation can be offered based on the hypothesis that the major portion of ethoxide is formed via parallel reaction of decomposition of 1a. Previous studies have shown that tetrabutylammonium...
fluoride solutions are strongly basic and the presence of water leads to the generation of hydroxide anions. At the same time N-nitrosocarbamates are known to be hydrolytically labile in such conditions. To verify the hypothesis, we conducted a trial experiment with ethyl N-butyl-N-nitrosocarbamate, which is a close structural analog of 1a but lacks a silicon center. An NMR sample of it in DMF-d7 was added to 5 equiv of Bu4NF·3H2O at 5 °C. The spectrum after 30 min indicated complete decomposition of the starting material with the almost exclusive formation of 6a, which in this case could occur only via basic hydrolysis of the starting N-nitrosocarbamate. Hence we are proposing a two-pathway decomposition for carbamates 1a–d in the presence of Bu4NF·3H2O, as reflected in Scheme 5. The significant differences in product composition between 1a and 1d are due to the presence of the bulky and branched t-butyl groups in 1d (Figs. 3 and 4), which render the carbonyl group virtually inaccessible, thus slowing down considerably the rate of basic hydrolysis.

3. Conclusions

Our efforts to date have led to the formulation and implementation of a new synthetic strategy aimed at the preparation and isolation of secondary N-nitrosocarbamates via desilylation of chemically and thermally stable tertiary N-2-(trimethylsilyl)ethyl-N-nitrosocarbamates.

The current article presents the first solid-state structural studies of N-nitrosocarbamates. X-ray data have demonstrated that both of the studied target structures exist as E conformers in the solid state, with a nearly planar N-nitrosocarbamate moiety. Further, DFT calculations demonstrate that the E orientation at the N-N bond is the preferred arrangement in the gas phase as well, for N-nitrosocarbamates, N-nitrosoureas and N-nitrosoamides.

Desilylation studies demonstrate that the process depends on several factors: temperature, solvent and concentration of fluoride anion. The current methodology, employing Bu4NF·3H2O, seems to be most effective in cases of structures with large and branched carbamate groups, whose steric hindrance effectively suppresses the competing process of basic hydrolysis of the N-nitrosocarbamate, the latter leading directly to the anions 6 rather than 3. Use of anhydrous fluoride ion sources, such as tetrabutylammonium triphenylpentafluorosilicate (TBA) or CsF/CsOH mixtures may prove advantageous in optimizing the yields of the N-nitrosocarbamate anions 3.

4. Experimental

1H and 13C spectra of intermediate and target compounds were recorded at 300 and 75 MHz, respectively, and referenced to the solvent (CDCl3: 7.27 ppm and 77.0 ppm; D2O: 4.76 ppm; acetonitrile-d3: 1.93 ppm; DMF-d7: 8.03 ppm). X-ray structures were obtained using an Oxford Diffraction Xcalibur3 diffractometer with graphite monochromatic Cu Kα radiation. Structure solution and refinement was preformed using the SHELXTL 6.10 software package. All calculations were performed utilizing the Gaussian03-Linda/GaussView software package on a Linux-operated cluster (QuantumCube QS4-2400C by Parallel Quantum Solutions, Fayetteville, AR). Constant temperature desilylation reactions were conducted using the Isotemp 1016S circulating bath. Elemental analysis was provided by Atlantic Microlab, Norcross, GA. HRMS data was provided by the Mass Spectrometry and Proteomics facility at the Ohio State University. Nitrosonium tetrafluoroborate was purchased from the Lancaster chemical company. 3-(Trimethylsilyl)propanamide and 2,4,6-tris(t-butyl)phenyl chloroformate were synthesized, following previously reported procedures. 2-(Trimethylsilyl)ethanamine (5) was prepared according to a published patent work. The 1H NMR data for compounds 4 and 5, and precursors to them, are reported in this article, as they were previously unavailable.

4.1. X-ray crystallography of 1-adamantyl N-2-trimethylsilyl-ethyl-N-nitrosocarbamate (1c)

A crystal (yellow plate) of 1c (C16H28N2O3Si) having approximate dimensions 0.324×0.206×0.083 mm was mounted on a glass fiber. The preliminary set of cell constants was calculated from reflections harvested from 5 sets of 15 frames, merged to 139 peaks that were used to derive the initial orientation matrix. Data acquisition was conducted at 150 K using the phi and omega scans technique. Final cell constants were determined based on the full data set, leading to a triclinic cell (P-1) with these dimensions: a=6.6116 (13) Å, b=9.8970 (18) Å, c=13.958 (2) Å, α=75.660 (14)°, β=84.856 (14)°, γ=89.407 (14)°, V=881.3 (3) Å³. For Z=2 and FW=324.49, the calculated density is 1.223 g/cm³. Non-hydrogen atoms were refined anisotropically; hydrogen atoms were assigned based on geometry. The final structure has values for the unweighted agreement factor R1=0.0459 based on 1300 strong reflections (I>4σ) and R1=0.0489 based on all data.
4.2. X-ray crystallography of 2,4,6-tris(2-butyl)phenyl N-2-trimethylsilyl ethyl-N-nitrosocarbamate (1d)

A crystal (yellow needle) of 1d (C₂₅H₂₃N₂O₃Si) having approximate dimensions 0.358 x 0.079 x 0.072 mm was mounted on a glass fiber. The preliminary set of cell constants was calculated from reflections harvested from 5 sets of 15 frames, merged to 155 peaks that were used to derive the initial orientation matrix. Data acquisition was conducted at 100 K using the phi and omega scans technique. Final cell constants were determined based on the full data set, leading to an orthorhombic cell (a) 24.18 Å, a = 90.00°, β = 90.00°, γ = 90.00°, V = 10647.2 (17) Å³. For Z = 16 and FW = 434.67, the calculated density is 1.075 g/cm³. Non-hydrogen atoms were refined anisotropically; hydrogen atoms were assigned based on geometry. The final structure has values for the unweighted agreement factor R1 = 0.0917 based on 7208 strong reflections ( Δ > 4σ) and R1 = 0.1193 based on all data.

4.3. Fluoride-assisted desilylation of ethyl N-2-(tri- methylsilyl)ethyl-N-nitrosocarbamate (1a) and 2,4,6-tris(2-butyl)phenyl N-2-(trimethylsilyl)ethyl-N-nitrosocarbamate (1d). General procedure

In a typical run 0.020 mol of carbamate 1, dissolved in 0.7 mL of the appropriate deuterated solvent (acetonitrile-d₃ or DMF-d₇), was added to Bu₄NF·3H₂O (0.020–0.10 mol, 1–5 equiv) at −15°C (ice-acetone bath). The resultant solution was transferred into an NMR tube and kept at the appropriate temperature until disappearance of the signals of the starting material. NMR measurements were conducted at regular time intervals. The change in quantity of reactant/product was monitored via integration of the NMR signals relative to the multiplet of Bu₄N⁺ centered at δ 1.76 ppm.

4.3.1. Ethyl N-nitrosocarbamate, tetrabutylammonium salt (3a–Bu₄N). ¹H NMR (DMF-d₇, anion only) δ 4.14 (q, J = 7.1 Hz, 2H), 1.23 (t, J = 7.1 Hz, 3H); ¹H NMR (acetonitrile-d₃, anion only) δ 4.09 (q, J = 7.1 Hz, 2H), 1.21 (t, J = 7.1 Hz, 3H).

4.3.2. 2,4,6-Tris(2-butyl)phenyl N-nitrosocarbamate, tetrabutylammonium salt (3d–Bu₄N). ¹H NMR (DMF-d₇, anion only) δ 7.34 (s, 2H), 1.43 (s, 18H), 1.31 (s, 9H).

4.3.3. 3-(Trimethylsilyl)propanamide (4). ³¹P NMR (CDCl₃) δ 2.80–2.87 (m, 2H), 0.91–0.97 (m, 2H), 0.03 (s, 9H).

(B) 3-(Trimethylsilyl)propanamide. ¹H NMR (CDCl₃) δ 5.61 (broad s, 2H), 2.17–2.24 (m, 2H), 0.80–0.87 (m, 2H), 0.02 (s, 9H).

4.3.4. 2-(Trimethylsilyl)ethanamine hydrochloride. ¹H NMR (CDCl₃) δ 2.94–3.01 (m, 2H), 0.84–0.91 (m, 2H), −0.03 (s, 9H).

(C) 2-(Trimethylsilyl)ethanamine. ¹H NMR (CDCl₃) δ 2.71–2.78 (m, 2H), 2.10 (broad s, 2H), 0.73–0.80 (m, 2H), −0.01 (s, 9H).

4.4. Preparation of N-2-(trimethylsilyl)ethylcarbamates. General procedure (Method A)

To a stirred solution of 3-(trimethylsilyl)propanamide (3.40 mmol) and mercuric acetate (4.60 mmol) in anhydrous N,N-dimethylformamide (10 mL), was added a solution of the corresponding alcohol (102.50 mmol) in anhydrous N,N-dimethylformamide (3 mL), at ambient temperature and under nitrogen. This was followed by addition of a solution of NBS (4.50 mol) in N,N-dimethylformamide (2 mL). The reaction was stirred for 12 h at room temperature. The solvents were removed at reduced pressure and methylene chloride (50 mL) was added to the residual solid. The organic extract was washed with water (5 x 25 mL), dried (MgSO₄) and the solvent was removed under reduced pressure. The resultant residue was passed through a short silica gel filter (hexane:ethyl acetate = 3:1) and the solvents were removed under reduced pressure to give the desired carbamate. Further purification via column chromatography (hexane: ethyl acetate = 3:1) led to isolated products that were >95% pure by NMR.

4.4.1. Ethyl N-2-trimethylsilyl ethylcarbamate (2a) (Method A). Yield: 85%. Colorless liquid: ¹H NMR (CDCl₃) δ 4.69 (bs, 1H), 4.10 (q, J = 7.0 Hz, 2H), 3.18–3.24 (m, 2H), 1.24 (t, J = 7.0 Hz, 3H), 0.77–0.83 (m, 2H), 0.01 (s, 9H); ¹C NMR (CDCl₃) δ 156.5, 60.6, 37.4, 18.2, 14.6, −1.7; HRMS (FAB⁺) m/z Caled for C₃₁H₅₀N₂O₃Si [M + Na⁺] 212.1083, found 212.1076.

4.4.2. t-Butyl N-2-trimethylsilyl ethylcarbamate (2b) (Method A). Yield: 36%. Colorless liquid: ¹H NMR (CDCl₃) δ 5.80 (bs, 1H), 3.10–3.19 (m, 2H), 1.41 (s, 9H), 0.81–0.87 (m, 2H), 0.04 (s, 9H); ¹C NMR (CDCl₃) δ 155.7, 79.0, 37.0, 28.4, 18.1, −1.7; HRMS (FAB⁺) m/z Caled for C₃₃H₅₁N₂O₃Si [M + Na⁺] 240.1396, found 240.1396. Anal. Caled for C₃₃H₅₁N₂O₃Si: C, 55.25%; H, 10.66; N, 6.44. Found: C, 55.50; H, 10.54; N, 6.14.

4.4.3. 1-Adamantyl N-2-trimethylsilyl ethylcarbamate (2c) (Method A). Yield: 50%. White solid: mp 92–94°C. ¹H NMR (CDCl₃) δ 4.42 (bs, 1H), 3.12–3.20 (m, 2H), 2.17 (m, 3H), 2.10 (m, 6H), 1.65 (m, 6H), 0.75–0.82 (m, 2H), 0.02 (s, 9H); ¹C NMR (CDCl₃) δ 155.4, 41.7, 37.0, 36.2, 30.8, 18.2, 11.2, −1.7; HRMS (FAB⁺) m/z Caled for C₃₈H₅₈N₂O₃Si [M + Na⁺] 318.1865, found 318.1876; Anal. Caled for C₃₈H₅₈N₂O₃Si: C, 65.03; H, 9.89; N, 4.74. Found: C, 65.24; H, 9.93; N, 4.58.

4.4.4. 2,4,6-Tris(2-butyl)phenyl N-2-trimethylsilyl ethylcarbamate (2d) (Method B). A solution of 2-(trimethylsilyl)ethanamine (0.22 g, 1.85 mmol) and pyridine (0.15 g, 1.85 mmol, 0.15 mL) in dichloromethane (5 mL) at 0°C (ice-water), followed by...
stirring at ambient temperature for 12 h. The mixture was washed with water, the organic layer was separated, dried (MgSO₄) and the solvent removed. The resultant residue was passed through a short silica gel filter and the product eluted with methylene chloride. The solvent was removed to yield the product as a white solid (0.34 g, 45%). Further purification via recrystallization from hexane, to yield white needles: mp 157–159 °C. ¹H NMR (CDCl₃) δ 7.31 (s, 2H), 4.99 (bs, 1H, NH), 3.28–3.36 (m, 2H), 1.37 (s, 18H), 1.32 (s, 9H), 0.88–0.94 (m, 2H), 0.06 (s, 9H); ¹³C NMR (CDCl₃) δ 155.2, 146.7, 145.7, 141.9, 123.1, 37.8, 35.6, 34.8, 31.52, 31.47, 18.4, –1.6; Anal. Calcd for C₂₈H₄₂N₂O₃Si: C, 71.23; H, 10.68; N, 3.45. Found: C, 71.23; H, 10.90; N, 3.45.

4.5. Preparation of N-2-trimethylsilyl-ethyl-N-nitroso-carbamates. General procedure (aqueous method)

To a solution of the corresponding alkyl N-2-(trimethylsilyl)ethylcarbamate 2a–c (1.25 mmol) in ether (2 mL) was added a solution of sodium nitrite (11.21 mmol) in water (2 mL). Without stirring or cooling, nitric acid (1.5 mL, 80%) was added a solution of sodium nitrite (11.21 mmol) in water (2 mL). The resultant solution was cooled to 5 °C, then added solid NOBF₄ (10.00 mmol) and the solvent removed to afford the corresponding alkyl N-nitroso-N-2-(trimethylsilyl)ethylcarbamate 1a–c. Further purification by column chromatography (silica gel, hexane: CH₂Cl₂ = 2:1) led to isolated products that were >95% pure by NMR.

4.6. Preparation of N-2-trimethylsilyl-ethyl-N-nitroso-carbamates. General procedure (anhydrous method)

To a stirred solution of the corresponding alkyl N-2-(trimethylsilyl)ethylcarbamate 2a–c (5.00 mmol) and anhydrous pyridine (10.00 mmol) in anhydrous acetonitrile (2.5 mL) at −20 °C, was added in one portion solid NOBF₄ (10.00 mmol). The solution was stirred at 0 °C under nitrogen for a period of 1–2 h and the progress of the reaction was followed by thin layer chromatography (hexane–CH₂Cl₂ = 2:1), the product exhibiting a rapidly moving yellow spot. The solvent was removed and the resultant mixture was passed through a short silica gel filter (hexane–CH₂Cl₂ = 2:1). Removal of the solvents at reduced pressure gave the product 1a–c that were >95% pure by NMR.

4.6.1. Ethyl N-2-trimethylsilyl-ethyl-N-nitroso-carbamate (1a). Yield: 72% by the aqueous method, 78% by the anhydrous method. Yellow liquid: ¹H NMR (CDCl₃) δ 4.53 (q, J = 7.3 Hz, 2H), 3.70–3.77 (m, 2H), 1.45 (t, J = 7.3 Hz, 3H), 0.65–0.72 (m, 2H), 0.03 (s, 9H); ¹H NMR (acetone-d₆) δ 4.43 (q, J = 7.0 Hz, 2H), 3.67–3.73 (m, 2H), 1.38 (t, J = 7.0 Hz, 3H), 0.63–0.68 (m, 2H), 0.01 (s, 9H); ¹H NMR (DMF-d₇) δ 4.54 (q, J = 7.2 Hz, 2H), 3.75–3.81 (m, 2H), 1.42 (t, J = 7.2 Hz, 3H), 0.67–0.73 (m, 2H), 0.05 (s, 9H); ¹³C NMR (CDCl₃) δ 153.7, 64.2, 37.6, 15.4, 14.2, –2.0; HRMS (FAB⁺) m/z Calcd for C₆H₁₄NO₃Si [M + Na⁺] + 241.0984, found 241.0981. Anal. Calcd for C₆H₁₄NO₃Si: C, 66.31; H, 9.74; N, 6.44. Found: C, 66.09; H, 9.77; N, 6.46.

4.6.2. t-Butyl N-2-trimethylsilyl-ethyl-N-nitroso-carbamate (1b). Yield: 69% by the aqueous method. Yellow liquid: ¹H NMR (CDCl₃) δ 3.68–3.74 (m, 2H), 1.65 (s, 9H), 0.66–0.72 (m, 2H), 0.04 (s, 9H); ¹H NMR (acetone-d₆) δ 3.65–3.72 (m, 2H), 1.60 (s, 9H), 0.63–0.69 (m, 2H), 0.01 (s, 9H); ¹³C NMR (CDCl₃) δ 152.0, 85.0, 37.4, 28.0, 15.5, –2.0; HRMS (FAB⁺) m/z Calcd for C₆H₁₈N₂O₃Si [M + Na⁺] + 269.1297, found 269.1301.

4.6.3. 1-Adamantyl N-2-trimethylsilyl-ethyl-N-nitroso-carbamate (1c). Yield: 30% by the aqueous method, 81% by the anhydrous method. Yellow solid, recrystallized from petroleum ether at −25 °C, to yield yellow plates: mp 98–99 °C. ¹H NMR (CDCl₃) δ 6.67–6.73 (m, 2H), 2.29 (m, 9H), 1.72 (m, 6H), 0.66–0.72 (m, 2H), 0.04 (s, 9H); ¹³C NMR (CDCl₃) δ 151.4, 85.0, 41.3, 37.4, 36.0, 31.0, 15.5, –1.9. Anal. Calcd for C₁₆H₂₈N₂O₃Si: C, 59.22; H, 8.70; N, 8.63. Found: C, 59.03; H, 8.73; N, 8.45.

4.6.4. 2,4,6-Tris(tert-butyl)phenyl N-2-trimethylsilyl-ethyl-N-nitroso-carbamate (1d). Carbamate 2d (0.23 g, 0.57 mmol) was dissolved in a mixture of acetic acid (3.0 mL) and acetic anhydride (4.5 mL). The resultant solution was cooled to 5 °C (ice-water) and NaNO₂ (0.83 g, 12.06 mmol) was added in small portions, over 2-h period, while keeping the temperature below 10 °C. Upon complete addition, the resultant mixture was stirred for additional 12 h at ambient temperature. The solvents were removed at reduced pressure and the residue was portioned between water and ether. The ether extract was stirred for 10 min with saturated aq NaHCO₃, the organic layer was separated, dried (MgSO₄) and the solvent removed at reduced pressure. The resultant yellow oil was flash chromatographed on a short silica gel column (hexane: methylene chloride = 5:1). The yellow colored, highly mobile fraction was collected and the solvent removed, leaving 0.21 g (84%) of the product as a yellow oil, which slowly solidified. Recrystallized from methanol at −30 °C to yield yellow needles: mp 62–64 °C. ¹H NMR (CDCl₃) δ 7.41 (s, 2H), 3.84–3.89 (m, 2H), 1.39 (s, 18H), 1.37 (s, 9H), 0.74–0.78 (m, 2H), 0.07 (s, 9H); ¹H NMR (acetone-d₆) δ 7.43 (s, 2H), 3.79–3.85 (m, 2H), 0.68–0.74 (m, 2H), 0.02 (s, 9H); ¹H NMR (DMF-d₇) δ 7.48 (s, 2H), 3.89–3.95 (m, 2H), 0.72–0.78 (m, 2H), 0.07 (s, 9H); ¹³C NMR (CDCl₃) δ 153.5, 148.0, 145.4, 141.4, 123.5, 37.9, 35.6, 34.9, 31.51, 31.48, 15.4, –2.0. Anal. Calcd for C₂₆H₂₉N₂O₃Si: C, 66.31; H, 9.74; N, 6.44. Found: C, 66.09; H, 9.77; N, 6.46.

5. Supporting information available

Crystallographic data (excluding structure factors) for the structures in this paper have been deposited with the Cambridge Crystallographic Data Centre as supplementary publication numbers CCDC 258576 and 258577. Copies of the data can be obtained, free of charge, on application to CCDC, 12 Union Road, Cambridge CB2 1EZ, UK [fax: +44-(0)1223-336033 or e-mail: deposit@ccdc.cam.ac.uk].

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**Supplementary data**

Energies and thermodynamic parameters of optimized minimum structures of compounds 1a–d, MNU and MNNB are summarized in Table S1. Images of 1H NMR spectra of compounds 1b and 2a are shown in Figure S1.

Supplementary data associated with this article can be found at 10.1016/j.tet.2005.03.044

**References and notes**

37. Yellow liquid: 1H NMR (CDCl3) δ 4.55 (q, JH, 2H), 3.75 (t, J = 7.1 Hz, 2H), 1.47 (t, J = 7.2 Hz, 3H), 1.33–1.43 (m, 2H), 1.18–1.30 (m, 2H), 0.89 (t, J = 7.2 Hz, 3H); 13C NMR (CDCl3) δ 154.0, 64.3, 40.7, 29.0, 20.0, 14.3, 13.5.