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Radical chain reactions of α-azido ketones with tributyltin hydride: reduction vs nitrogen insertion and 1,2-hydrogen shift in the intermediate *N*-stannylaminyl radicals

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Abstract—The radical chain reactions of a variety of acyclic and cyclic α-azido ketones with tributyltin hydride have been investigated. The derived *N*-(tributylstannyl)aminyl radicals normally undergo H-abstraction reaction yielding corresponding amines, and thence symmetrical pyrazines by subsequent self-condensation, in competition with 1,2-H-migration from the α-carbon to nitrogen leading to α-imino ketone decomposition products with loss of the chain-carrying tributyltin radical. The noteworthy occurrence of a quite uncommon radical 1,2-hydrogen-atom shift is considered to be largely due to consequent formation of a highly stable, captodative carbon-centred radical. In contrast with our previous *N*-stannylaminyl radicals produced from α-azido-β-keto esters, the present aminyl congeners give poor amounts (or even none) of nitrogen-inserted amides/lactams, which are envisaged to arise from intramolecular three-membered cyclisation onto the ketone moiety followed by β-scission of the resultant alkoxyl radical. It is inferred that adequate stabilisation of the eventual ring-opened carbon radical be a major factor for the successful outcome of the regiospecific nitrogen insertion process. Evidence is also presented that chemoselective attack of tris(trimethylsilyl)silyl radical to the ketone oxygen of an α-azido ketone gives rise to deazidation as a likely consequence of β-elimination of azidyl radical by the ensuing α-silyloxyalkyl radical. X-Ray crystal structure analyses of the bromo ketone **5a**, the azido ketone **5b**, the caprolactam **22**, and the pyrazine **26** have been performed.

1. Introduction

Organic azides are versatile nitrogen intermediates whose reactivity and synthetic potential have been investigated extensively under thermal and photochemical conditions both in the presence and in the absence of nucleophilic or electrophilic species.[1] On the other hand, radical reactions of the organic azides have been by far less explored, though recent studies have revealed that radical species can add to the α- or γ-position of the azido moiety to give an aminyl radical after loss of molecular nitrogen by the initial 1,3- and/or 3,3-triazenyl adduct.[2] Intramolecular additions of carbon-centred radicals, including the aryl,[3] thiocarbonyl,[4] alkyl,[5] and vinyl[6] members, to alkyl and aryl azides have been shown to provide useful synthetic routes to *N*-heterocycles. Moreover, very recently the intermolecular addition of alkyl radicals to sulfonyl azides has been exploited in two preparatively attractive methods for the radical azidation of alkyl iodides and dithiocarbonates.[7] Among heteroatom-centred radicals, especially the stannyl ones exhibit a fair tendency to react with azides yielding *N*-stannyl-substituted aminyl radicals, which act as the key intermediates in several important synthetic processes. In fact, the radical chain reactions of tributyltin hydride (Bu_3SnH) with alkyl and acyl azides result in straightforward production of reduced amines[8,9] or rearranged imines[10] through transient *N*-(tributylstannyl)-aminyl radicals. Similar chain reactions of allylstannanes with sulfonyl azides result in smooth allylation of the derived *N*-(tributylstannyl)sulfonamidyl radicals.[2] Moreover, *N*-tributyltin-substituted aminyl radicals, being somewhat nucleophilic than ordinary aminyl radicals,[9] are highly capable of performing intramolecular five- and six-membered cyclisation onto carbonyl groups to give otherwise inaccessible medium-sized lactams by β-fragmentation of the ensuing alkoxyl radicals.[11] Following these data, very recently we provided a novel entry to amides and lactams through regiospecific nitrogen insertion of β-keto ester compounds by using the radical chain reactions of the α-azido derivatives with Bu_3SnH.[12] In such circumstances the derived stannylaminyl radical undergoes 3-*exo* cyclisation onto the adjacent ketone group to form an alkoxyl radical, which then undergoes β-scission and eventual reduction of the ring-opened radical (Scheme 1).

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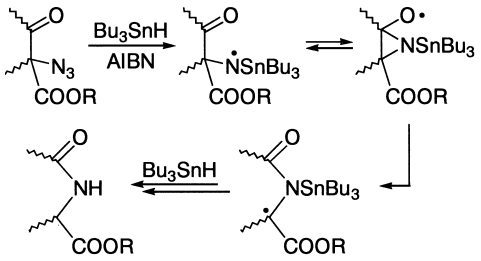


Scheme 1. Nitrogen insertion mechanism in α-azido-β-ketoesters.

The driving force of the regiospecific β-scission would be provided by resonance stabilisation of the amide group formed and, additionally, by the formation of the captodatively stabilised ring-opened radical. However, in certain cases the occurrence of the nitrogen insertion process was seriously limited by competing reduction of stannylaminyl radical to amine and/or noticeable deazidation of the keto ester substrate by the stannyl radical.

In light of our interesting findings with α-azido-β-keto esters, we next were prompted to extend our study to analogous radical chain reactions of simple α-azido ketones. We, in fact, became interested in gaining further useful information about the attractive reactivity of (tributylstannyl)aminyl radicals toward ketone groups and, especially, in ascertaining whether our previous nitrogen insertion method might similarly apply to that type of keto azide, despite the fact that, owing to lack of the ester substituent, no captodative stabilisation of the eventual ring-opened intermediate would be provided. Herein we report our results with the acyclic and cyclic azido ketones **1b**–**7b** which are shown in Chart 1.

2. Results and discussion

The already known azides **1b**–**4b**,**6b**,**7b** were readily prepared by α-bromination of the parent ketones **1a**–**4a**,**6a**,**7a** and subsequent displacement of bromide by azide ion, by using a procedure similar to that we had previously employed to prepare the α-azido derivatives of

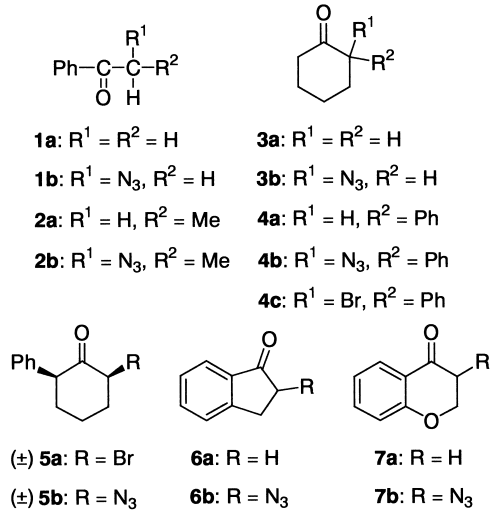


Chart 1.

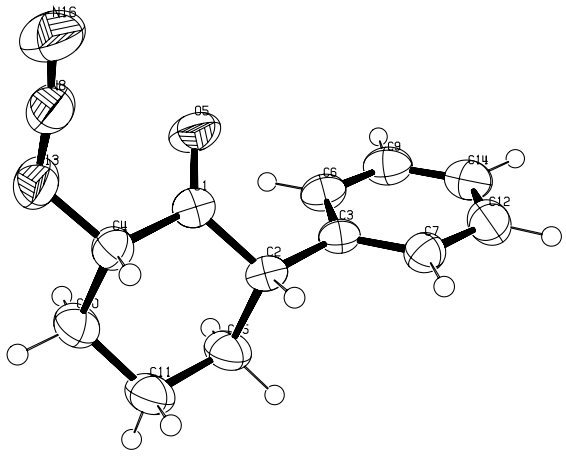
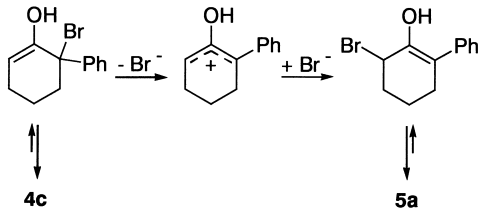


Figure 1. The X-ray molecular structure of **5b** showing the atom-numbering scheme.

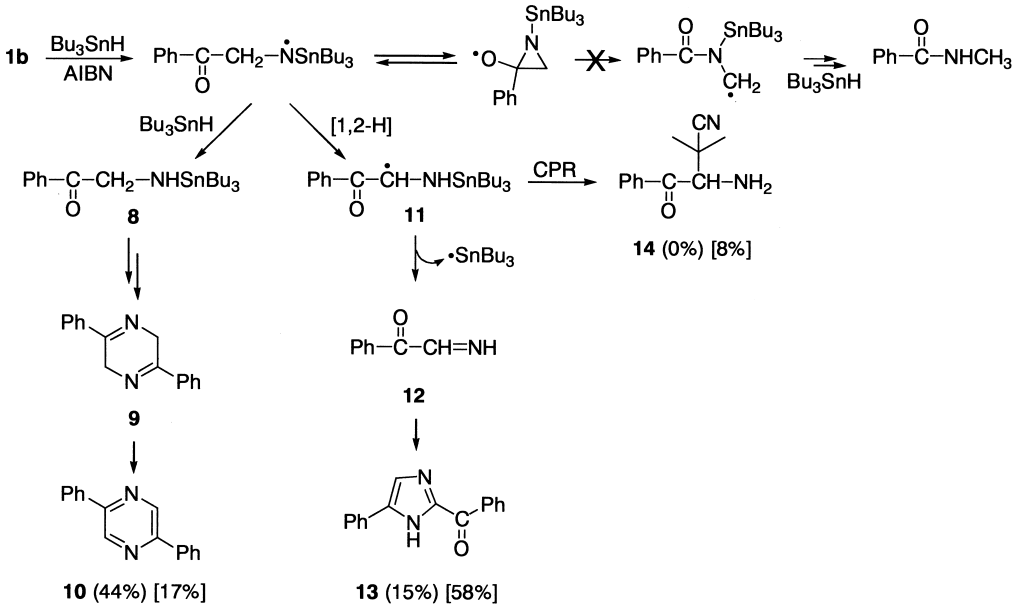
β-keto esters. The hitherto unknown 2-azido-6-phenylcyclohexanone **5b**, whose structure was fully established by X-ray crystallographic analysis (Fig. 1), was obtained in the nearly exclusive *cis*-configuration upon reaction of the corresponding *cis*-bromide **5a** with sodium azide in DMSO. The bromide **5a** was in turn obtained in a stereoselective fashion by spontaneous isomerisation of the bromide **4c** (over ca. 12 days at room temperature), probably through initial enolisation and subsequent ionisation yielding an allylic carbonium ion (Scheme 2). The observed retention of configuration in the conversion of *cis*-bromide **5a** into *cis*-azide **5b** might be the result of the intervention of an S_N1 mechanism and/or isomerisation of the *trans*- into the thermodinamically more stable *cis*-isomer through enolisation. All the prepared azides were preliminarily proven to show no evident sign of decomposition when being heated in refluxing benzene.

All the azides **1b**–**7b** were reacted with Bu_3SnH (1.1 equiv.) in refluxing benzene in the presence of 2,2′-azobis(2-methylpropionitrile) (AIBN, 0.1 equiv.), using conditions strictly comparable with those previously employed for the corresponding reactions of azido keto esters (Procedure A). The reactions were normally prolonged for ca. 3–5 h and the crude mixtures were then directly subjected to column chromatography. Since our present azides, but to an extent largely dependent upon their structural features, appeared to yield α-imino ketone products with release of the chain-carrying tributyltin radical, we were led to investigate the possible effect of using a catalytic amount of the hydride reagent under high dilution conditions (Procedure B).

The reaction of phenacyl azide **1b** with Bu_3SnH, following



Scheme 2. Bromide migration in ketone **4c**.

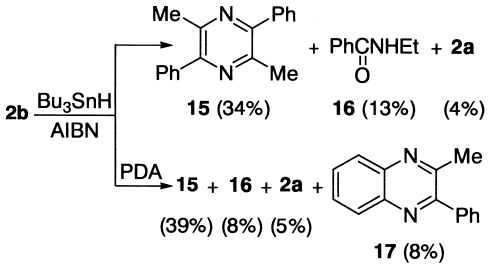


Scheme 3. Reaction pathways for phenacyl azide **1b**. Yields in round brackets refer to Procedure A, yields in square brackets refer to Procedure B.

Procedure A, gave no evidence at all for any production of *N*-methylbenzamide, which was the expected product of regiospecific nitrogen insertion, but instead gave the diphenylpyrazine **10** as well as minor amounts of the imidazole **13** as the only identifiable products (Scheme 3).

In another experiment the resulting crude reaction mixture allowed direct crystallisation of the dihydropyrazine **9**; such compound **9** was found to be fairly stable in the solid state, but it underwent fairly rapid aromatisation to **10** in benzene solution. The dihydropyrazine **9** (and thence the aromatised compound **10**) was presumably due to self-condensation of the stannylated amino ketone **8**, which could be formed by a viable H-abstraction reaction of the derived stannylaminyl radical with the tin hydride (Scheme 3). In fact, symmetrical pyrazines, including the pyrazine **10**, are known to form by the spontaneous self-condensation of α-amino ketones produced in situ by reduction of the corresponding azides.[13] Interestingly, the imidazole **13** was instead presumably due to self-condensation of an alternate α-imino ketone intermediate **12**. Although formation of the imidazole **13** by dimerisation of the compound **12** has been previously described,[14] it is worth noting that it occurred by rearrangement of an initial nitrene, obtained by pyrolysis of phenacyl azide **1b** at 180–200°C. In our case, we suggest that also the presumed imine **12** should be attributed to a transient stannylaminyl radical. Indeed, the intermediate **12** might in principle result from a radical 1,2-H rearrangement from carbon to nitrogen, followed by β-elimination of the chain-carrying tributyltin radical from the resultant captodative radical **11** (Scheme 3). Radical 1,2-H-migrations are quite unusual in carbon-centred radicals,[15] whereas such type of migration possibly occurs, but to a (very) limited extent, in the *N*-stannylaminyl radicals that are formed upon addition of tributyltin radicals to simple alkyl azides.[9] In fact, the radical reaction of terminal alkyl azides with Bu_3SnH normally affords aldehydes in variable amounts, depending on the nature of the substrate. The actual mechanism for the conversion of azides to aldehydes is still unclear, but the reaction is likely to proceed via intermediate imines.[9] The imino ketone **12** might have also been arisen from a competing process promoted by some base present in the reaction medium (possibly the amine **8**). α-Azido ketones having α-hydrogens are indeed known to be base-sensitive and undergo base-promoted loss of nitrogen to form α-imino ketones (or 1,2-diketones by hydrolysis)[16] and/or tautomeric α-amino enones.[17] However, we ascertained that phenacyl azide **1b**, when being heated in refluxing benzene in the presence of even 1 equiv. of triethylamine, could just suffer conversion into imidazole **13** at a very low rate. Indeed, no trace of **13** was observed after 3 h (the time required for complete disappearance of the starting azide in the radical reaction) and a yield as low as 10% was obtained only after 8 h. Consequently, a possible intervention of a base-promoted process during the radical reaction of azide **1b** was believed to be unimportant.

With the aim of achieving some solid support to the believed radical occurrence of the imine **12**, the above reaction of phenacyl azide **1b** was repeated by performing very slow addition of 0.3 equiv. of the tin hydride by syringe pump over ca. 3 h (Procedure B). Using such a reduced amount of Bu_3SnH the azide **1b** could still undergo virtually complete reaction, this fact being consistent with some catalytic role being played by the hydride. Moreover, using such a very low concentration of the hydride there was preferential occurrence of the imidazole **13** at the expense of the competing pyrazine **10**: this is consistent with expected enhancement of the unimolecular aminyl radical rearrangement at the expense of the bimolecular reduction. Additionally, the reaction also afforded a significant amount of the amine **14**, which is plausibly formed by trapping of the rearranged radical **11** by the 2-cyano-2-propyl radical (CPR) arising from fragmentation of AIBN (Scheme 3). These overall data furnished sound support to our view that an initial stannylaminyl radical should be primarily involved in the formation of the presumed intermediate **12**



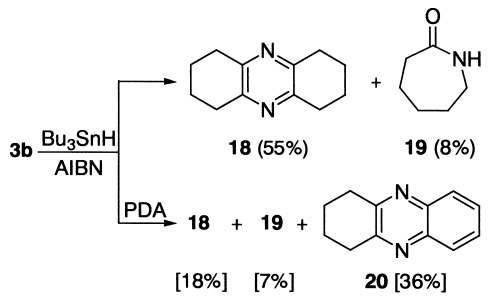
Scheme 4. Reaction products of phenacyl azide **2b**. Yields in brackets refer to Procedure A.

and thence of the isolated imidazole **13**. Consequently, these data also provided the first convincing evidence in favour of 1,2-H transfer reaction in *N*-tributylstannyl-substituted aminyl radicals.

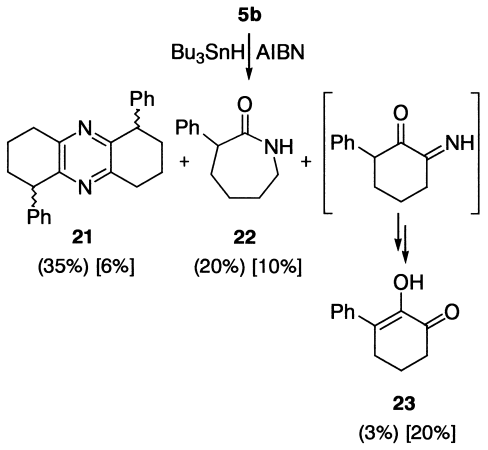
It is worth noting that another radical route to the imine **12** might involve intermolecular H-transfer from the stannylated amine **8** to the primary stannylaminyl radical. Although this pathway cannot be totally excluded, however we consider it unimportant, since it seems unlikely that amine **8** could act as a better hydrogen donor than the stannane.

The stannylaminyl radical derived from phenacyl azide **1b** is thus not capable of performing regiospecific nitrogen insertion to give *N*-methylbenzamide, probably since the required β-fragmentation of the alkoxyl radical intermediate would form a poorly stable, primary α-aminoalkyl radical (Scheme 3). The same stannylaminyl radical is instead interestingly prone to exhibit smooth H-shift from carbon to adjacent nitrogen, probably owing to consequent formation of a highly stable carbon radical such as the captodative radical **11**. That rearrangement can compete efficiently with hydrogen transfer from the hydride and becomes even preferred if the hydride concentration is suitably lowered.

The reaction of the methylated phenacyl azide **2b**, under the standard conditions of Procedure A, similarly furnished the corresponding pyrazine **15** in a comparable yield with that of the above diphenylpyrazine **10**, but, interestingly, it concomitantly furnished a significant amount of the nitrogen-inserted benzamide **16**. The reaction gave also a small amount of the ketone **2a**, whose formation can be ascribed to a known deazidation process involving preliminary attack of the stannyl radical to the terminal azide nitrogen.[12] No diagnostic evidence for any occurrence of an



Scheme 5. Reaction products of azide **3b**. Yields in round brackets refer to Procedure A, yields in square brackets refer to Procedure B.



Scheme 6. Reaction products of azide **5b**. Yields in round brackets refer to Procedure A, yields in square brackets refer to Procedure B.

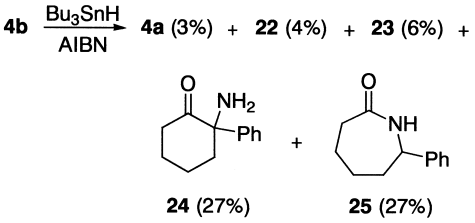
imino propanone analog of the imino ethanone **12** was obtained (Scheme 4).

In an attempt to intercept the possibly formed imino propanone we then repeated the reaction in the presence of *o*-phenylenediamine (PDA). This aromatic diamine is in fact known to trap reactive α-imino ketones, yielding condensed quinoxaline products.[18] In the presence of PDA we actually succeeded in isolating the disubstituted quinoxaline **17**, albeit in a poor yield (Scheme 4), thus proving that some production of unstable 1-phenyl-2-iminopropanone should have evidently occurred.

Therefore, the aminyl radical arising from the azide **2b**, similar to the one formed from **1b**, can undergo both H-abstraction reaction, to give the corresponding amine, and 1,2-H-migration, to give a rearranged imine. However, this radical was also enabled to perform nitrogen insertion yielding the amide **16**, although to a limited extent. Evidently, in such case the regiospecific β-scission of the cyclised alkoxyl radical becomes rather feasible since it can form a secondary aminoalkyl radical somewhat more stable than the primary one obtainable from **1b**.

Our successive findings obtained with the cyclic azide **3b** revealed that the respective aminyl radical behaves in a fashion similar to that displayed by the radical congener produced from the acyclic counterpart **2b**. When the azide **3b** was in fact reacted with the tin hydride according to Procedure A, the tricyclic pyrazine **18** was obtained in relatively high yield along with a small amount of the ring expanded caprolactam **19** (Scheme 5). Moreover, when the reaction was repeated using Procedure B and in the presence of PDA, the formation of **18** was found to be largely depressed in favour of the tetrahydrophenazine **20**, that under these conditions was formed to a noticeable extent as a result of effective trapping of labile α-iminocyclohexanone[19] by the aromatic diamine (Scheme 5).

The stannylaminyl radicals that were subsequently produced from the isomeric phenyl-substituted 2-azidocyclohexanones **4b** and **5b** showed a (much) higher tendency to give rise to their nitrogen-inserted lactam products. The usual reaction of the 2-azido-6-phenylcyclo-



Scheme 7. Reaction products of azide **4b**. Yields in brackets refer to Procedure A.

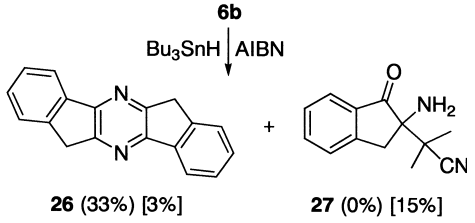
hexanone **5b** indeed led to isolation of the pyrazine **21**, which still occurred as the major product, together with the caprolactam **22**, which was obtained in a comparable, significant yield. This reaction also afforded a small amount of the hydroxyenone **23**, which was the hydrolytic product of the corresponding phenyl-substituted α-imino-cyclohexanone (Scheme 6).

It is worth noting that, in line with similar evidence provided by the above azides **1b** and **3b**, the alternate use of Procedure B resulted in marked suppression of pyrazine **21**, and to some extent of lactam **22**, in favour of enone **23** (and, plausibly, of its imino ketone precursor) (Scheme 6).

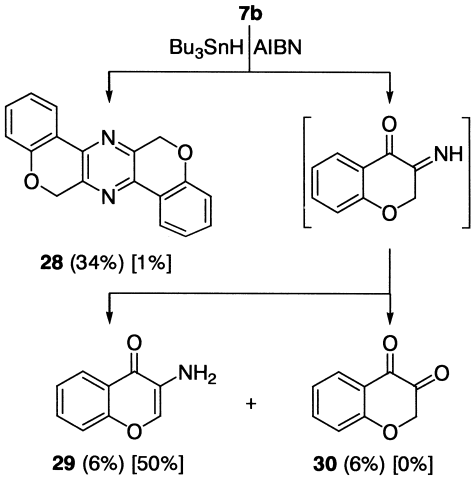
The isomeric 2-azido-2-phenylcyclohexanone **4b** led to isolation of the respective caprolactam **25** in a yield synthetically useful and identical to that of the reduced amine **24**, that was seemingly unable to undergo self-condensation to pyrazine (Scheme 7).

Whereas the marked propensity of the aminyl radical obtained from **4b** to yield the corresponding caprolactam **25** is likely ascribable to fair stability of the tertiary benzyl radical formed by usual fragmentation of the alkoxyl radical precursor, at this stage we have no convincing explanation for the enhanced tendency seemingly displayed by the aminyl radical of the cyclohexanone azide **5b** to give rise to its caprolactam **22**.[20]

It is worth noting that the azide **4b**, besides affording the amine **24** and the lactam **25** (as well as some deazidated ketone **4a**), additionally gave small amounts of the isomeric lactam **22** and the enone **23** (Scheme 7), thus suggesting that under the reaction conditions the azide itself could also undergo isomerisation to **5b**. In a control experiment, TLC actually showed that the initial production of the compounds **24** and **25** was accompanied by concomitant formation of the azide isomer **5b**. It is possible that the observed isomerisation of **4b** to **5b** might proceed through a mechanism similar to that above postulated for the related



Scheme 8. Reaction products of azide **6b**. Yields in round brackets refer to Procedure A, yields in square brackets refer to Procedure B.



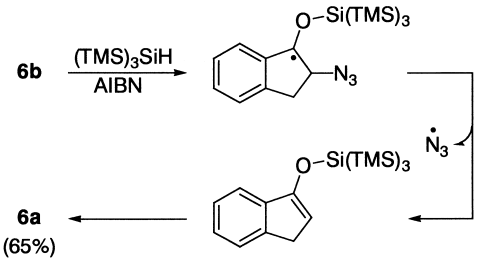
Scheme 9. Reaction products of azide **7b**. Yields in round brackets refer to Procedure A, yields in square brackets refer to Procedure B.

conversion of 2-bromo-2-phenylcyclohexanone **4c** into the 6-bromide **5a** (Scheme 2). However, in the case of the azide **4b**, the presence of the stannane would play some activating role in view of the fact that **4b** remained totally unchanged in refluxing benzene in the absence of the stannane.

Despite their analogies with the above congeners, the stannylaminyl radicals obtained from the benzocyclic azidoalkanones **6b** and **7b** were curiously highly reluctant to exhibit any nitrogen insertion process. Under the conditions of Procedure A, the indanone azide **6b** gave the pyrazine **26** as the sole identifiable product (Scheme 8), whereas the chromanone azide **7b**, in addition to its pyrazine **28**, also furnished small amounts of the enamine **29** and the dione **30**. These latter compounds were the expected products of tautomerisation and hydrolysis of an initially formed iminochromanone (Scheme 9).

Under the alternate conditions of Procedure B, the azide **6b** only allowed isolation of a modest yield of the aminoindanone **27**, ascribable to coupling between CPR and the captodative radical deriving from the stannylaminyl radical by 1,2-H-shift (Scheme 8). The azide **7b**, instead, only gave the enamine **29** to a noticeable extent (Scheme 9). We suggest that the aminyl radicals derived from these benzocyclic azides, owing to possible conformational restraints, are essentially discouraged to afford their cyclised alkoxyl adducts and thence only undergo H-abstraction and/or additional 1,2-H-shift. Once again, for both reactions, high-dilution conditions make the hydrogen atom migration the major process of the reaction mechanism.

In a search for a possible extension of our α-azido ketone reactions, in the present work we briefly studied the radical chain reactions of tris(trimethylsilyl)silane with the indanone azide **6b** and also with 2-ethoxycarbonyl-1-tetralone azide.[12] In light of the previous findings of Kim and co-workers that azides are relatively inert toward tris(trimethylsilyl)silyl radicals,[5] the silyl radical was expected to add selectively on the ketone oxygen rather than on the azido moiety. We therefore aimed at investigating whether the resultant α-(silyloxy)alkyl radical could be able to perform intramolecular 3-*exo* cyclisation onto the adjacent



Scheme 10. Reaction of azide **6b** with silyl radicals.

azido group to form a synthetically attractive aminyl radical by subsequent loss of nitrogen. However, treatment of **6b** with a slight excess of $(TMS)_3SiH$ and a catalytic amount of AIBN in refluxing benzene gave only the deazidated indanone **6a** in fairly good yield. Strictly comparable results were obtained from the same reaction with 1-tetralone azide. In both cases the derived oxyalkyl radical was therefore seemingly able to perform only β-elimination of azidyl radical to give an intermediate enol ether and hence the deazidated substrate by eventual hydrolysis (Scheme 10).

3. Conclusions

Our overall present and previous findings have shown that the radical chain reactions of Bu_3SnH with α-azido ketones can usefully afford amides and lactams provided that the alkoxyl radical arising from 3-*exo* cyclisation of a transient (tributylstannyl)aminyl radical onto the ketone moiety could undergo β-scission to form an adequately stabilised carbon radical. Very efficient or fair stabilisation can be furnished by ester[12] or aryl (**4b**) moieties, respectively, whereas alkyl groups can provide stabilisation only to some extent (**2b**, **3b**, **5b**). The outcome of the nitrogen insertion process can however be limited by the possible occurrence of conformational restraints in the 3-*exo* cyclisation step, as suggested for compounds **6b** and **7b**.

When the driving force of the nitrogen insertion is not strong enough, the competitive reduction of the original stannylaminyl radical leads to an α-amino ketone and then to the corresponding symmetrical pyrazine, provided that no additional substituent is present in the precursor α-position (like in **4b**).

The most noteworthy findings are that the stannylaminyl radicals are normally found to yield α-imino ketone decomposition products as a result of unusually easy 1,2-H-migration, whose driving force is essentially ascribable to the consequent formation of a captodative, highly stabilised carbon-centred radical.[21] The occurrence of this rearrangement, already suggested for similar intermediates but never proved, was definitely supported by the results of the reactions carried out under catalytic conditions. Indeed, a 1,2-H-shift followed by loss of a tributyltin radical is consistent with the complete disappearance of the starting azide when using significantly less then 1 equiv. of Bu_3SnH (Procedure B). The observed enhancement of the yields of α-imino ketone decomposition products at the expense of the pyrazines is also consistent with the occurrence of a unimolecular mechanism competing with the bimolecular aminyl reduction. Moreover, trapping of the rearranged captodative radical by CPR, which was observed with two different azides (**1b**, **6b**), provides an additional, ultimate proof of the migration.

Finally, the present work has also shown that when using tris(trimethylsilyl)silane in place of the tin hydride the radical reaction of an α-azido ketone would only result in deazidation, owing to preferred elimination of azidyl radical by the resultant α-(silyloxy)alkyl radical.

4. Experimental

4.1. General procedures

All melting points (Kofler melting point apparatus) are uncorrected. ^1H and ^{13}C NMR spectra were normally carried out in $CDCl_3$ solutions, using tetramethylsilane as the internal standard. Mass spectra were determined by the electron impact method (70 eV). IR spectra were recorded in $CHCl_3$ solutions. Column chromatography was performed on ICN silica gel (63–200 Å) by gradual elution with light petroleum (bp 40–70°C)/diethyl ether and/or ethyl acetate/diethyl ether mixtures and final elution with ethyl acetate/diethyl ether/methanol mixtures.

4.2. Materials

The starting ketones **1a**–**7a**, caprolactam **19**, as well as *n*-tributyltin hydride were commercially available, and were used as received. 2,2′-Azobis(2-methylpropionitrile) (AIBN, Fluka) and dibenzoyl peroxide (DBP) were recrystallised from $CHCl_3/CH_3OH$.

2-Azido-1-phenyl-1-propanone (**2b**) was prepared according to the literature.[22] The already known azido ketones **1b**, **3b**, **4b**, and **7b** were prepared in 70–85% yield through bromination of the parent ketones **1a**, **3a**, **4a**, **7a** with *N*-bromosuccinimide (NBS, 1 equiv.) and a catalytic amount of DBP in refluxing tetrachloromethane (15 min–10 h) and subsequent treatment of the crude bromide with sodium azide (2 equiv.) in dimethyl sulfoxide (DMSO).[12] The azidoindanone **6b** was similarly prepared from the corresponding bromide, in turn obtained by treatment of indanone **6a** with bromine (1 equiv.) in diethyl ether at room temperature.

The azides **1b**, **3b**, **6b**, and **7b** had spectral data consistent with those previously reported.[23a] Analytical data of azide **4b** were as follows: mp 27–28°C (lit,[24] an oil), ν_{max} 2099 (N_3), 1717 (CO) cm^{-1}, 300 MHz ^1H NMR δ 1.62–2.02 (5H, m), 2.32–2.54 (2H, m), 2.78–2.85 (1H, m), 7.27–7.50 (5H, m), 50 MHz ^{13}C NMR δ 21.92, 27.45, 36.34, 39.91, 74.46 (q), 126.72, 129.05, 129.42, 135.20 (q), 206.93 (q).

Hitherto unknown *cis*-2-azido-6-phenylcyclohexanone (**5b**) was similarly prepared by reacting sodium azide in DMSO with the *cis*-bromide **5a**, which was available by spontaneous isomerisation of the bromide **4c** both in the solid state and in solution (over ca. 12 days at room temperature). The bromide **5a** had: mp 102–103°C, 300 MHz ^1H NMR δ 1.91–2.40 (5H, m), 2.74 (1H, m), 3.70 (1H, br dd,

J_1=5.6 Hz, J_2=12.4 Hz), 4.78 (1H, ddd, J_1=6.0 Hz, J_2=12.4 Hz, J_3=1.0 Hz), 7.10–7.40 (5H, m), 50 MHz ^{13}C NMR δ 27.09, 36.07, 40.91, 57.25, 57.73, 128.04, 129.08, 129.28, 138.22 (q), 200.78 (q). Anal. calcd for $C_{12}H_{13}BrO$: C, 56.94; H, 5.18; Br, 31.57. Found: C, 56.86; H, 5.17; Br, 31.51. The structure of **5a** was confirmed by X-ray diffraction.

The azide **5b** had: mp 72–74°C, ν_{max} 2105 (N_3), 1731 (CO) cm^{-1}, 200 MHz ^{1}H NMR δ 1.70–2.13 (4H, m), 2.21–3.49 (2H, m), 3.55–3.68 (1H, m), 4.00–4.12 (1H, m), 7.10–7.40 (5H, m), 50 MHz ^{13}C NMR δ 24.32, 35.17, 36.25, 57.62, 66.63, 128.87, 130.11, 130.38, 138.77 (q), 206.94 (q). The structure of **5b** was confirmed by X-ray diffraction.

All the prepared azides **1b**–**7b** were found to be quite stable in refluxing benzene. In refluxing benzene and in the presence of 1 equiv. of triethylamine the phenacyl azide **1b** was found to remain virtually unchanged over ca. 3 h, but to suffer some decomposition to imidazole **13** (ca. 10%) after 8 h.

The known reaction products **10**,[25] **15**,[26] **16**,[27] **17**,[28] **18**,[29] **20**,[30] **22**,[31] **23**,[32] **24**,[33] and **25**[34] were authenticated by spectral comparison with the literature data. 2-Benzoyl-5-phenylimidazole (**13**),[14,35] caprolactam **19** and 3-amino-4H-chromen-4-one (**29**)[23b] were identified by spectral comparison with authentic samples. The dione **30** was identified following a procedure reported in the literature.[36]

4.3. Reactions of azido ketones with tributyltin hydride

4.3.1. Procedure A. A benzene (80 mL) solution containing the appropriate keto azide (4 mmol), the tin hydride (4.4 mmol), and AIBN (0.4 mmol) was refluxed under a nitrogen atmosphere for 3–5 h, until TLC or IR monitored the virtual disappearance of the starting azide. In the case of azide **2b**, the reaction was carried out also in the presence of *o*-phenylenediamine (2 mmol) (Scheme 4).

4.3.2. Procedure B. A benzene (12 mL) solution of Bu_3SnH (1.2 mmol) and AIBN (0.4 mmol) was added by a syringe pump over 3 h to a refluxed benzene (65 mL) solution containing the appropriate keto azide (4 mmol) under a nitrogen atmosphere. The resulting mixture was refluxed for additional 3–5 h until the virtual disappearance of the starting azide. In the case of azide **3b**, the reaction was performed in the presence of *o*-phenylenediamine (2 mmol) (Scheme 5).

4.3.3. Reactions. All the reactions performed according to Procedure A were monitored by ^{1}H NMR and found to exhibit the intermediate formation of unstable dihydropyrazines, being normally converted to the corresponding aromatised compounds by air oxidation. In the reaction of the azide **1b** the resultant 3,6-diphenyl-2,5-dihydropyrazine (**9**) could be actually isolated as a solid compound upon addition of pentane to a diethyl ether solution of the crude reaction mixture. The compound **9**, stable in the solid state but fairly rapidly oxidisable in solution, had: mp 169–170°C, 200 MHz ^{1}H NMR δ 4.76 (4H, s), 7.31–7.50 (6H, m), 7.72–7.89 (4H, m), 50 MHz ^{13}C NMR δ 50.06, 126.11, 128.56, 130.48, 141.19 (q), 165.55 (q), MS *m/e* (rel. inten.) 234 (M^+, 48), 131 (100), 103 (92). Anal. calcd for $C_{16}H_{14}N_2$: C, 82.02; H, 6.02; N, 11.96. Found: C, 81.95; H, 6.01; N, 12.00.

Using Procedure A or B, the reaction mixture was eventually concentrated under reduced pressure and the resultant residue was normally subjected to direct column chromatography. In the reaction of azide **7b**, following procedure A, chromatographic product separation proved to be quite difficult due to slow oxidation of the resulting dihydropyrazine (M^+, 290), attempted oxidisation of this compound by bubbled air resulted in essential production of an unidentified compound (M^+, 306).

Yields of the isolated products **2a**, **4a**, **10**, **13**–**30** are given in Schemes 3–9. Analytical data of the new compounds **14**, **21**, **26**–**28** were as follows.

4.3.4. 3-Amino-2,2-dimethyl-4-oxo-4-phenylbutanenitrile (14). Oil, ν_{max} 3380, 3310 (NH_2), 2239 (CN), 1680 (CO) cm^{-1}, 200 MHz ^{1}H NMR δ 1.38 (3H, s), 1.45 (3H, s), 1.90 (2H, br s), 4.39 (1H, s), 7.47–7.54 (2H, m), 7.60–7.64 (1H, m), 7.94–8.02 (2H, m), 50 MHz ^{13}C NMR δ 23.79, 25.15, 37.91 (q), 59.70, 123.84 (q), 129.26, 129.64, 134.72, 136.81 (q), 199.39 (q). Anal. calcd for $C_{12}H_{14}N_2O$: C, 71.26; H, 6.98; N, 13.85. Found: C, 71.18; H, 6.98; N, 13.82.

4.3.5. 1,6-Diphenyl-1,2,3,4,6,7,8,9-octahydrophenazine (21). (Seemingly one stereoisomer) mp 170–172°C, 200 MHz ^{1}H NMR δ 1.70–2.35 (8H, m), 2.73–3.09 (4H, m), 4.33 (2H, t, J=6.0 Hz), 6.95–7.08 (4H, m), 7.19–7.44 (6H, m), 50 MHz ^{13}C NMR δ 19.69, 32.31, 33.00, 47.57, 126.71, 128.88, 129.45, 146.19 (q), 151.49 (q), 151.61 (q). MS *m/e* (rel. inten.) 340 (M^+, 100). Anal. calcd for $C_{24}H_{24}N_2$: C, 84.67; H, 7.11; N, 8.23. Found: C, 84.81; H, 7.09; N, 8.30.

4.3.6. 6,12-Dihydrodiindeno[1,2-*b*:1,2-*e*]pyrazine (26). Mp 268–269°C, 200 MHz ^{1}H NMR δ 4.04 (4H, s), 7.41–7.56 (4H, m), 7.60–7.67 (2H, m), 8.09–8.15 (2H, m), 50 MHz ^{13}C NMR δ 39.98, 121.00, 125.43, 127.67, 129.07, 138.84 (q), 142.12 (q), 151.60 (q), 157.18 (q). MS *m/e* (rel. inten.) 256 (M^+, 100). Anal. calcd for $C_{18}H_{12}N_2$: C, 84.35; H, 4.72; N, 10.93. Found: C, 84.50; H, 4.70; N, 10.96. The structure of **26** was confirmed by X-ray diffraction.

4.3.7. 2-(2-Amino-1-oxo-2,3-dihydro-1*H*-inden-2-yl)-2-methyl-propanenitrile (27). Oil, ν_{max} 3381, 3308 (NH_2), 2221 (CN), 1713 (CO) cm^{-1}, 300 MHz ^{1}H NMR δ 1.30 (3H, s), 1.52 (3H, s), 2.80 (2H, br s), 3.05 (1H, d, J=17.8 Hz), 3.54 (1H, d, J=17.8 Hz), 7.37–7.49 (2H, m), 7.66 (1H, m), 7.77 (1H, d, J=7.6 Hz), 75.5 MHz ^{13}C NMR δ 21.76, 23.01, 40.73 (q), 41.01, 65.21 (q), 124.19 (q), 125.44, 126.98, 128.93, 135.71 (q), 136.72, 151.3 (q), 205.89 (q). MS *m/e* (rel. inten.) 146 ($M^+ - C(CH_3)_2CN$, 100). Anal. calcd for $C_{13}H_{14}N_2O$: C, 72.87; H, 6.59; N, 13.07. Found: C, 72.75; H, 6.62; N, 13.15.

4.3.8. 6,13-Dihydrodichromeno[3,4-*b*:3,4-*e*]pyrazine (28). Mp 264–266°C, 300 MHz ^{1}H NMR δ 5.41 (4H, s), 6.98–7.22 (4H, m), 7.30–7.41 (2H, m), 8.11–8.20 (2H, m). MS *m/e* (rel. inten.) 288 (M^+, 100). Anal. calcd for

$C_{18}H_{12}N_2O_2$: C, 74.99; H, 4.20; N, 9.72. Found: C, 74.89; H, 4.20; N, 9.70.

4.4. Reactions of azidoindanone 6b and 2-azido-2-ethoxycarbonyl-1-tetralone with tris(trimethylsilyl)-silane

A benzene (40 mL) solution of the azide **6b** (2 mmol) was treated with the silane (2.2 mmol) and AIBN (0.2 mmol) and then refluxed for 3 h. Removal of the solvent and column chromatography of the residue gave the deazidated indanone **6a** in 65% yield. Using the same procedure, the azidotetralone[12] gave the deazidated compound[12] in 74% isolated yield.

4.5. X-Ray crystallographic analyses

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 175948 (**5a**), CCDC 175949 (**26**), CCDC 175950 (**22**), and CCDC 175951 (**5b**). 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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