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Relative migratory aptitudes of hydrogen, benzoyl, 4-methoxyphenyl and 4-nitrophenyl groups in some unsaturated carbenes (vinylidenes)

Ferenc Bertha,[a] József Fetter,[a,*] Károly Lempert,[a,b] Mária Kajtár-Peredy,[c] Gábor Czira[d] and Ernő Koltai[e]

[a]*Department of Organic Chemistry, Budapest University of Technology and Economics,[†] H-1521 Budapest, Hungary*
[b]*Research Group for Alkaloid Chemistry, Hungarian Academy of Sciences, H-1521 Budapest, Hungary*
[c]*Institute of Chemistry, Chemical Research Center, Hungarian Academy of Sciences, H-1525 Budapest, Hungary*
[d]*Gedeon Richter Chemical Works, Ltd, H-1475 Budapest, Hungary*
[e]*Isotope Institute Co., Ltd, H-1121 Budapest, Hungary*

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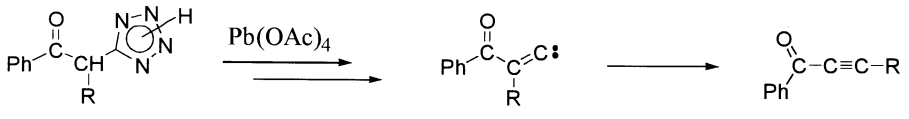
Abstract—([5-^{13}C] Tetrazol-5-yl)methyl ketones were prepared and subjected to oxidative fragmentation induced by lead tetraacetate. The resulting intermediate [1-^{13}C]-3-oxoprop-1-en-1-ylidenes rearrange, depending on the relative migratory aptitudes of the benzoyl group and the ligands R, either to [3-^{13}C]prop-2-yn-1-ones or to [2-^{13}C]prop-2-yn-1-ones or to mixtures of the two isomers. The ^{1}H and/or ^{13}C NMR spectra of the products allow the three cases to be distinguished. The relative migratory aptitudes were found to be H>PhCO, 4-MeOC$_6$H$_4$>4-O$_2$NC$_6$H$_4$.

1. Introduction

Recently tetrazol-5-ylmethyl ketones **1a–c** (and a series of analogs with other R groups and/or other electron withdrawing groups replacing the benzoyl group) were found to afford, on treatment with lead tetraacetate (LTA), the corresponding ynones **3**.[1] 3-Oxoprop-1-en-1-ylidenes **2**, hitherto scarcely known[2] special types of unsaturated carbenes[3] (vinylidenes) were shown to be the intermediates of the reaction; rearrangement of the latter by [1,2] migration of either the benzoyl group or the R group then leads to the final products **3** (Scheme 1).

Similarly to the saturated carbenes, the vinylidenes are known to be unstable reactive intermediates which easily undergo [1,2] rearrangements to afford acetylenes.[3–12] However, in contrast to the case of the saturated carbenes, where the relative migratory aptitudes of various groups and hydrogen attached to C2 are well known (the order for the singlet carbenes being in general H>aryl>alkyl[13–15]) very little is known[10,16] about the relative migratory aptitudes of substituents attached to C2 of vinylidenes.

Equally little is known about the migratory aptitudes of acyl (and aroyl) groups both in saturated carbenes and vinylidenes. Thus, e.g. both the type **4** singlet carbenes and singlet carbene **6** (obtained by in situ thermolysis of the corresponding diazo compounds) rearrange with migration of their acyl groups to afford triketones **5** and the quinoline-2(1*H*)-one **7**, respectively (Scheme 2).[17] The observations that migration of the acyl groups in compounds **4** takes place in preference to migration of the methyl and hydroxyl groups (as well as to an, in principle, equally possible Wolff rearrangement), and in compound **6** in preference to that of



1 **2** **3**

Scheme 1. Oxidation of tetrazolylmethyl ketones **1** with lead tetraacetate. **1–3**: (a) R=H; (b) R=4-MeOC$_6$H$_4$ (PMP); (c) R=4-O$_2$NC$_6$H$_4$ (PNP).

Keywords: carbenes; benzoyl vinylidenes; migratory aptitudes; ^{13}C labelling.
* Corresponding author. Tel.: +36-1-463-2356; fax: +36-1-463-3296; e-mail: fetter.szk@chem.bme.hu
† Formerly Technical University Budapest.

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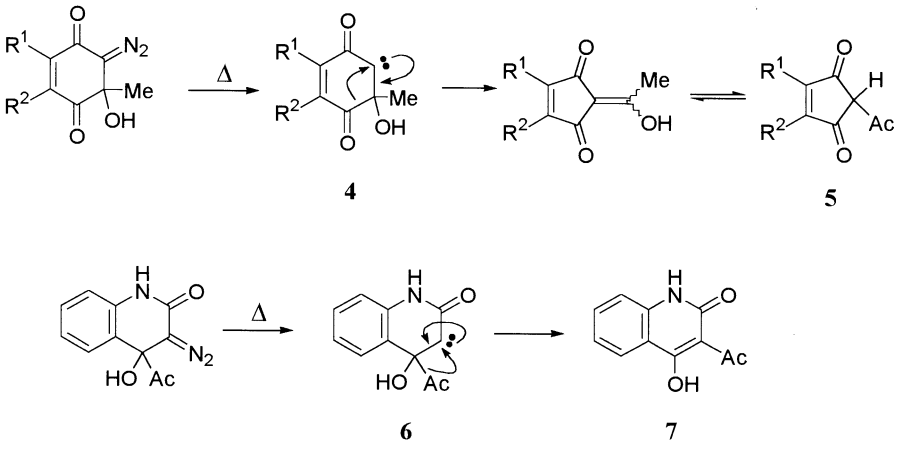
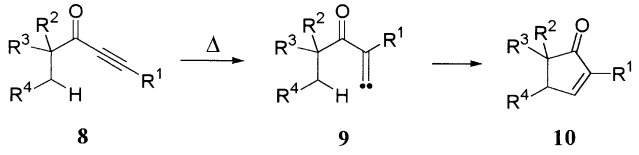


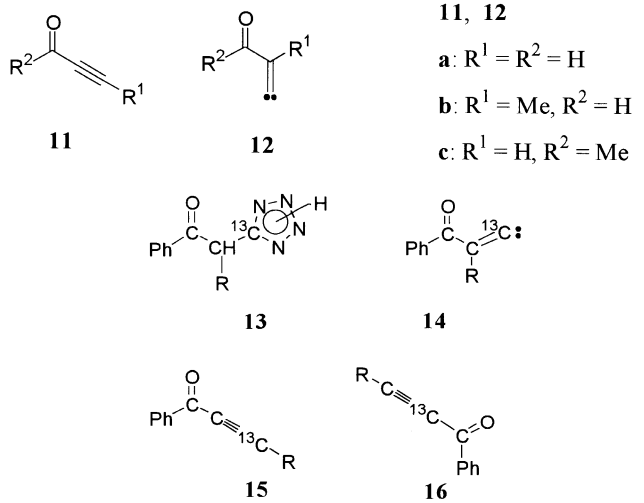
Scheme 2. Rearrangement of in situ prepared singlet carbenes **4** and **6.**

the aryl and hydroxyl group, however, do not necessarily reflect the orders of the inherent migratory aptitudes of acyl, the methyl, an aryl and the hydroxyl groups since migration of the acyl group in compounds **4** involves, and that of the aryl group in compound **6** would involve, in contrast to the migration of the two other groups competing for migration, concomitant ring contraction.

On the other hand, Dreiding and coworkers have found that gas-phase thermolysis of open-chain α-alkynones **8** and their cyclic analogs (with R^3+R^4 completing a five- or six-membered ring) afford, through the intermediacy of singlet 3-oxoalk-1-en-1-ylidenes (2-oxoalkylidene carbenes, **9**), by insertion of the carbene carbon atom into a CH group in appropriate position, cyclopent-2-enones **10**



Scheme 3. Alkynone cyclization. R^1=H, D, Me, Ph, $SiMe_3$; R^2=H, Me.



13–16 , **a**: R = H , **b**: R = 4-$MeOC_6H_4$, **c**: R = 4-$O_2NC_6H_4$

as the principal products (Scheme 3).[2] Rearrangement **8→9** is clearly the reverse of rearrangement **2→3** and may, in principle, take place by migration of either of the two groups attached to the acetylenic carbon atoms, the situation being, thus, similar as in rearrangement **2→3**. A theoretical study of the rearrangements of propynal (**11a**), but-2-ynal (**11b**) and butynone (**11c**) into the corresponding singlet carbenes **12a–c** (none of which is able to undergo cyclization to cyclopent-2-enones) has revealed that, under thermolysis conditions, 'a H-atom or an alkyl group competes favorably with an acyl group in the [1,2]-shift from α-alkynones to the corresponding acylvinylidenes'.[2c]

In view of the situation outlined we decided to establish experimentally the relative migratory aptitudes of the benzoyl group, the hydrogen atom, the 4-methoxyphenyl and the 4-nitrophenyl groups in 3-oxoprop-1-en-1-ylidenes **2a–c** generated in situ by oxidation of tetrazole derivatives **1a–c**. To this end, analogs **13a–c** of compounds **1a–c**, labelled by ^{13}C in position 5 of the tetrazole ring were prepared and subjected to LTA oxidation. Depending on the relative migratory aptitudes of the benzoyl group and the ligands R, the intermediate [1-^{13}C]-3-oxoprop-1-en-1-ylidenes **14** should furnish either [3-^{13}C]- (**15**) or [2-^{13}C]-prop-2-ynones (**16**) or mixtures of the two isomers, and the three cases should be readily distinguished by the NMR spectra.

2. Results and discussion

2.1. Preparation of the ([5-^{13}C]tetrazol-5-yl)methyl ketones 13a–c

The ^{13}C-labelled tetrazole derivatives **13a–c** were obtained from the corresponding ^{13}C-labelled nitriles **17a–c** by treatment with $AlCl_3$ and NaN_3 in THF, cf. Ref. 18. Nitriles **17a–c**, in turn, were prepared from phenacyl bromide and $K^{13}CN$, and by benzoylating 4-methoxyphenyl- and 4-nitrophenyl[^{13}C]acetonitrile, respectively, **17b** and **17c** existing, according to their IR and NMR spectra, partly or exclusively as the enols.

The reactions of the non-labelled analogs of cyanoketones **17b** and **17c** with $AlCl_3$ and NaN_3 in refluxing THF were

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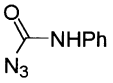
a: R = H, **b**: R = PMP, **c**: R = PNP



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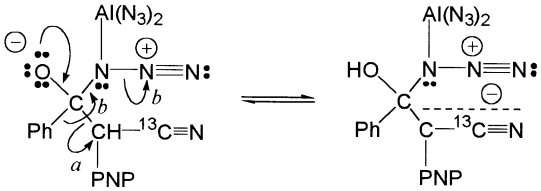
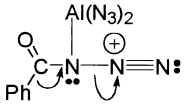


19c



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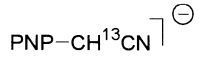
found to be very slow and particularly the yield of the resulting tetrazole derivative **1c** was rather low.[1] It was now found that the conversion of the labelled cyanoketone **17b** into tetrazole derivative **13b** can be considerably accelerated by increasing the amount of $AlCl_3$ used. A careful analysis of the product obtained from the reaction of the labelled cyanoketone **17c** with $AlCl_3$ and NaN_3 in THF under the conditions used for the preparation of the non-labelled tetrazole derivative **1c**[1] has, on the other hand, led to the detection of two further products, viz phenylcarbamoyl azide (**18**, 28%) and 4-nitrophenylaceto[^{13}C]nitrile (36%) in addition to the expected labelled tetrazole derivative **13c** (39%).

The formation of the two unexpected co-products may be understood by considering, in addition to the attack at the nitrile group of **17c** (leading to compound **13c**), the possibility of competitive attack of the azide at the carbonyl carbon atom,[‡] facilitated by the powerful electron withdrawing activity of the PNP group in compound **17c** and leading to intermediate **19c** which is analogous to the first intermediate of the Schmidt reaction[19] of ketones with HN_3. Alternatively, **19c** may be formed from the enol by attack of the reagent at the carbon atom in β-position relative to the [^{13}C]cyano group. Instead of following the normal course of the Schmidt reaction (path b) adduct **19c** reacts differently: again due to the powerful electron withdrawing ability of the PNP group which exerts a significant stabilizing effect on the resulting anion **21**, the central CC bond of the adduct is heterolytically cleaved (path a). The resulting two fragments, **20** and **21** are subsequently converted into phenyl isocyanate and 4-nitrophenylaceto[^{13}C]nitrile, respectively. Reaction of the isocyanate with a second molecule of $Al(N_3)_3$ affords adduct **22** which is the aluminium derivative of **18**, the azide of a monosubstituted carbamic acid and, therefore, in contrast to intermediate **20**, does not undergo the Curtius rearrangement.[20]



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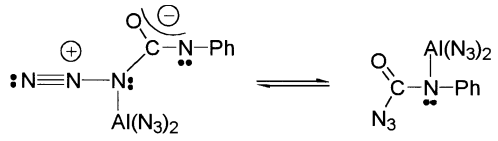

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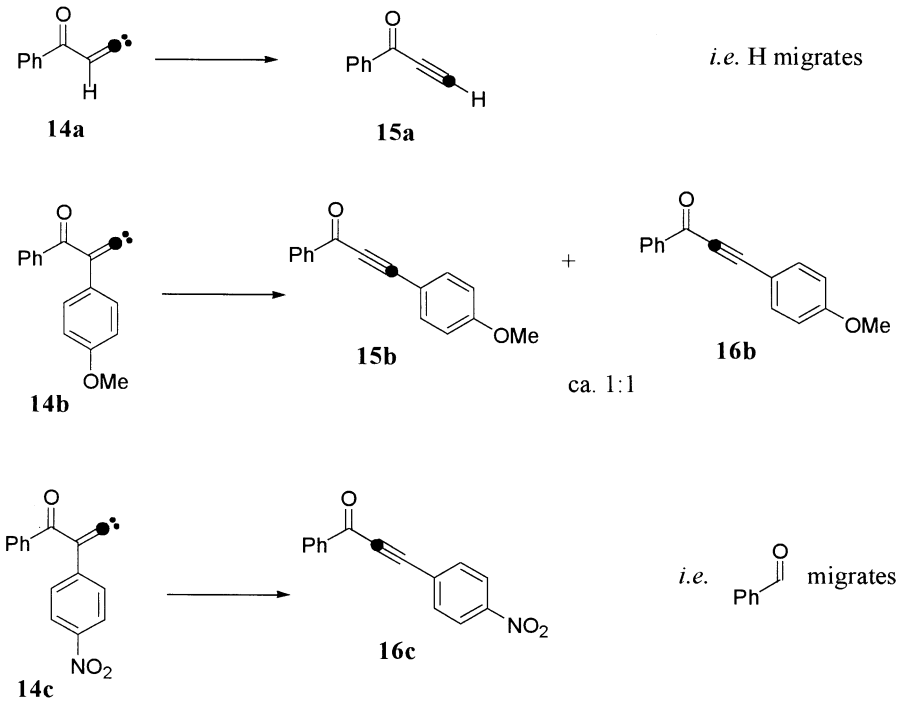
2.2. LTA oxidation of the ([5-^{13}C]tetrazol-5-yl)methyl ketones 13a–c

Oxidative fragmentations induced by LTA of tetrazole derivatives **13a–c** both afforded single products, while an approximately 1:1 mixture of two isomers was obtained on similar treatment of tetrazole derivative **13b**. The structures (**15** and/or **16**) of all these products were derived from their ^{1}H and/or ^{13}C NMR spectra.

Thus, the ^{1}H and ^{13}C NMR spectra of the oxidation products obtained from compound **13a** and from its non-labelled analog, compound **1a** were almost identical, except for the multiplicities of some signals; viz (i) in the ^{1}H NMR spectrum ($CDCl_3$) of the labelled oxidation product the singlet at δ 3.44 ppm of the acetylenic proton of the non-labelled oxidation product **3a** was replaced by a doublet (δ 3.44 ppm, $^1J_{C,H}$=255 Hz). In addition, a weak singlet at δ 3.44 ppm was also present, indicating that the labelled oxidation product (and, therefore, its precursor **13a** as well) were contaminated by about 15% of non-labelled material. (ii) In the ^{13}C NMR spectrum ($CDCl_3$) of the labelled oxidation product the singlet at δ 177.38 ppm of the carbonyl carbon atom of the non-labelled oxidation product **3a** was replaced by a doublet (δ 177.39 ppm, $^2J_{C,C}$=13.0 Hz). From these data structure **15a** follows unequivocally for the oxidation product of the labelled compound **13a** which shows that in the intermediate [1-^{13}C]3-phenyl-3-oxoprop-1-ene-1-ylidene **14a** (and therefore in its non-labelled analog **2a** as well) the hydrogen atom migrates in preference to the benzoyl group (Scheme 4).

Similarly, several signals in the ^{13}C NMR spectrum ($CDCl_3$) of the oxidation product of compound **13c** are doublets (whereas the corresponding signals in the spectrum of its non-labelled analog **3c** are singlets), viz the signal of C1 of the 4-nitrophenyl (PNP) group at δ 126.81 ppm ($^2J_{C,C}$=11.4 Hz), the common signal of C2 and C6 of the PNP group at δ 133.67 ppm ($^3J_{C,C}$=3.0 Hz), as well as the signals of C1 of the phenyl group at δ 136.42 ppm

[‡] The reagent is tentatively formulated as $Al(N_3)_3$, but the same result would be obtained if it were formulated as HN_3 or $N_3^{\ominus}$.



Scheme 4. Rearrangement of in situ prepared vinylidenes **14a–c**.

($^2J_{C,C}$=19.1 Hz) and of the carbonyl carbon at δ 177.36 ppm ($^1J_{C,C}$=90 Hz). Therefore the structure of the oxidation product of compound **13c** is **16c** which proves that in the intermediate [1-^{13}C]3-oxoprop-1-en-1-ylidene **14c** (and therefore in its non-labelled analog **2c** as well) the benzoyl group migrates in preference to the 4-nitrophenyl group.

The oxidation product of compound **13b** differs from those of compounds **13a** and **13c** in that the patterns of several signals in its ^{13}C NMR spectrum are those of two independent doublets of approximately equal intensities but with different coupling constants, viz the signals of C1 of the 4-methoxyphenyl (PMP) group at 111.92 ppm ($^1J_{C,C}$=90.8 Hz and $^2J_{C,C}$=12.2 Hz, respectively), of C1 of the phenyl group at 137.09 ppm ($^3J_{C,C}$=2.3 Hz and $^2J_{C,C}$=19.1 Hz, respectively) and of the carbonyl carbon atom at 178.00 ppm ($^2J_{C,C}$=13.4 Hz and $^1J_{C,C}$=91.9 Hz, respectively). This shows the oxidation product of compound **13b** to be an approximately 1:1 mixture of isomers **15b** and **16b**, and the migratory aptitudes of the PMP and the benzoyl groups in the intermediate [1-^{13}C]3-oxoprop-1-en-1-ylidene **14b** (and therefore in its non-labelled analog **2b** as well) to be roughly equal.

Thus, the conclusion may be drawn that the order of migratory aptitudes in the [1-^{13}C]3-oxoprop-1-en-1-ylidenes **14** (and their non-labelled analogs **2**) is H>PhCO, 4-MeOC$_6$H$_4$>4-O$_2$NC$_6$H$_4$.

3. Experimental

3.1. General

All reactions were monitored by TLC (DC-Alufolien 60 PF_{254}, Merck) and allowed to go to completion. The purity of the products was checked, in combination with IR spectroscopy, by TLC on DC-Alufolien 60 PF_{254}; the individual compounds were detected by UV irradiation or by using iodine or 5% ethanolic molybdophosphoric acid as the reagents.

All new crystalline compounds described in the present paper, except for those noted, were colorless. Mps were determined on a Kofler hot-stage mp apparatus and are uncorrected. IR spectra were recorded on a Specord 75 spectrometer (Zeiss, Jena), ^{1}H and ^{13}C NMR spectra were obtained with a Unity INOVA-400 spectrometer, using tetramethylsilane as the reference. *J*-values are given in Hz. Exact molecular mass determinations were made at 70 eV with a Finnigan-MAT 95 SQ hybride-tandem instrument using a heated direct inlet system and PFK (perfluorokerosene) as the reference.

The ^{13}C content of the K^{13}CN samples (prepared from Ba^{13}CO$_3$) used for the syntheses in the a and in the other two series was 85 and 95 atom%, respectively. The ^{13}C content of the various organic products prepared was checked by mass spectrometry at 70 and/or 20 eV with the Finnigan-MAT instrument mentioned; the values obtained were in agreement with the ^{13}C content of the K^{13}CN sample used for the synthesis of the particular product.

3.1.1. ([^{13}C]Cyano)methyl phenyl ketone (17a). The title compound [200 mg, 90%; mp 78°C, lit.[21] mp of the non-labelled analog 78–80°C; ν_{max} (cm^{-1}) 2260 (^{13}C≡N), 1690 (C=O), non-labelled analog, prepared for comparison 2260 (C≡N), 1695 (C=O), lit.22 2210, 1700] was obtained from phenacyl bromide (300 mg, 1.5 mmol) as described[22] for the preparation of the non-labelled analog, except for using K^{13}CN instead of KCN.

3.1.2. ([^{13}C]Cyano)(4-methoxyphenyl)methyl phenyl ketone (17b). (a) 4-Methoxybenzyl [^{13}C]cyanide was obtained as an oil in quantitative yield essentially as described in literature,[23] except for starting with 4-methoxybenzyl chloride (0.73 g, 11 mmol) rather than the bromide.

(b) A mixture of the above crude product (1.7 g, 11 mmol), methyl benzoate (1.6 g, 12 mmol), THF (9 cm^3) and 60% NaH (in paraffin oil; 0.89 g, 22 mmol) was refluxed for 1.5 h and worked up as described[1] for the preparation of the non-labelled analog to afford the title compound as a pale yellow oil which, in the crystalline state, exists as a mixture of the enol and keto forms while, in $CDCl_3$ solution, it exists in the keto form 2.05 g, 72%; mp 81°C. lit.[24] mp of the non-labelled analog 85–88°C; HRMS, found M$^{\cdot+}$ 252.0976, $C_{15}{}^{13}CH_{13}NO_2$ requires *m/z* 252.0980; ν_{max} (cm^{-1}) (KBr) 3170 br (OH, enol), 2220 (^{13}C≡N), 1690w (C═O); non-labelled compound (prepared according to Ref. 1) 3160 br, 2240, 1690 w; δ_H ($CDCl_3$) 3.78 (3H, s, OMe), 5.55 (1H, d, $^2J_{C,H}$=10.4 Hz COC*H*^{13}CN), 6.90+7.34 (2×2H, AA′BB′, J_O=8.6 Hz, PMP), 7.45 (2H, m, 3-H+5-H, Ph), 7.58 (1H, m, 4-H, Ph), 7.94 (2H, m, 2-H+6-H, Ph); δ_C ($CDCl_3$) 45.96 (d, $^1J_{C,C}$=61.8 Hz, CO–*C*–^{13}C), 55.36 (OMe), 115.10 (C3+C5, PMP), 116.77 (^{13}CN), 122.18 (d, $^2J_{C,C}$=3.8 Hz, C1, PMP), 128.99 and 129.44 (C3+C5 and C2+C6, Ph), 129.50 (d, $^3J_{C,C}$=3.0 Hz, C2+C6, PMP), 133.72 (C1, Ph), 134.30 (C4, Ph), 160.15 (C4, PMP), 189.09 (d, $^2J_{C,C}$=2.3 Hz, CO).

3.1.3. ([^{13}C]Cyano)(4-nitrophenyl)methyl phenyl ketone (17c). (a) Phenylaceto[^{13}C]nitrile was obtained from benzyl chloride and K^{13}CN as described[25] for the preparation of the non-labelled analog.

(b) 4-Nitrophenylaceto[^{13}C]nitrile (off-white crystals, 95%, crude; mp 105–106°C, lit.[26] mp of the non-labelled analog 115–116°C) was obtained by nitration of the above product as described[26] for the preparation of the non-labelled analog.

(c) The title compound (yellowish crystals, 45%; mp 163–164°C; HRMS, found M$^{\cdot+}$ 267.0723, $C_{14}{}^{13}CH_{10}N_2O_3$ requires 267.0725) which, in the crystalline state, exists as the pure enol [ν_{max} (cm^{-1}) (KBr) 3050 br (OH), 2200 (^{13}C≡N), 1540 vs+1340 vs (NO_2)] was obtained as described[27] for the preparation of the non-labelled analog [mp[27] 163.5°C; ν_{max} (cm^{-1}) (KBr) 3025br (OH), 2260 (C≡N), 1530 vs+1340 vs (NO_2)].

3.1.4. Phenyl ([5-^{13}C]tetrazol-5-yl)methyl ketone (13a). [94%, crude; mp, crude 184–187°C, lit. mp[1] of the non-labelled analog 187–188°C (MeOH); R_f values in TLC. of the labelled and non-labelled compound were identical] was obtained from compound **17a** as described[1] for the preparation of its non-labelled analog, except for starting with the ^{13}C-labelled nitrile **17a** instead of its non-labelled analog.

3.1.5. (4-Methoxyphenyl) ([5-^{13}C]tetrazol-5-yl)methyl phenyl ketone (13b). A mixture of compound **17b** (2.0 g, 7.9 mmol), $AlCl_3$ (1.33 g, 10 mmol), NaN_3 (2.35 g, 36 mmol) and dry THF (40 cm^3) was refluxed for 6 days. Since, according to TLC, considerable amounts of unchanged starting **17b** were still present, a further amount of $AlCl_3$ (1.0 g, 7.5 mmol; total amount 2.2 mmol/mmol **17b**) was added. After refluxing for a couple of hours, the starting compound was consumed and the mixture was worked up as described[1] for the preparation of the non-labelled analog to afford the title compound [72%; colorless amorphous solid foam; HRMS, found M$^{\cdot+}$ 295.1145, $C_{15}{}^{13}CH_{14}N_4O_2$ requires 295.1150; ν_{max} (cm^{-1}) (KBr) 3300–2600 (with several local maxima; NH), 1690 (C═O), practically identical with the spectrum of the non-labelled analog prepared similarly; δ_H ($CDCl_3$) 3.67 (3H, s, OMe), 6.76 (1H, d, $^2J_{C,H}$=7.2 Hz, COC*H*^{13}C), 6.77+7.34 (2×2H, AA′BB′, J_O=8.8 Hz, PMP), 7.41 (2H, m, 3-H+5-H, Ph), 7.54 (1H, m, 4-H, Ph), 8.02 (2H, m, 2-H+6-H, Ph), 13.5 (br, NH), except for the multiplicity of the 6.76 ppm signal, practically identical with the spectrum of the non-labelled analog;[1] δ_C ($CDCl_3$) 48.69 (d, $^1J_{C,C}$=58.7 Hz, CO*C*H^{13}C), 55.23 (OMe), 115.22 (C3+C5, PMP), 125.94 (d, $^2J_{C,C}$=3.8 Hz, C1, PMP) 128.97 and 129.33 (C3+C5 and C2+C6, Ph), 129.46 (d, $^3J_{C,C}$=2.3 Hz, C2+C6, PMP), 134.30 (C4, Ph), 134.53 (d, $^3J_{C,C}$=1.5 Hz, C1, Ph), 154.88 (^{13}C5, tetrazole), 159.72 (C4, PMP), 194.97 (d, $^2J_{C,C}$=2.3 Hz, C═O)].

3.1.6. (4-Nitrophenyl) ([5-^{13}C]tetrazol-5-yl)methyl phenyl ketone (13c), phenylcarbamoyl azide and 4-nitrophenylaceto[^{13}C]nitrile. Compound **17c** (0.93 g, 3.5 mmol) was allowed to react with $AlCl_3$ and NaN_3 in dry THF under argon as described[1] for the preparation of the non-labelled analog of compound **13c**, except that the reaction time was increased to 6 days. The mixture was evaporated to dryness; the residue was triturated with water and acidified with conc. HCl. The resulting thick emulsion was extracted with EtOAc. The EtOAc solution was dried ($MgSO_4$) and worked up by flash chromatography (Kieselgel 60 G, Merck; CH_2Cl_2→CH_2Cl_2–MeOH, 1:1) to obtain first a mixture (0.41 g) of phenylcarbamoyl azide [0.16 g, 28%; mp 102–103°C; HRMS, found M$^{\cdot+}$ 162.0534 and 119.0371, $C_7H_6N_4O$ requires 162.0541, C_7H_5NO (phenyl isocyanate, apparently formed in the mass spectrometer by thermolysis of the azide) requires 119.0371; ν_{max} (cm^{-1}) (KBr) 3330 (NH), 2160 (N_3), 1695 (C═O); δ_H ($CDCl_3$+DMSO-d_6) 7.08 (1H, m, 4-H, Ph), 7.29 (2H, m, 3-H+5-H, Ph), 7.52 (2H, br d, J_O=8.2 Hz, 2-H+6-H, Ph), 8.75 (br, NH); δ_C ($CDCl_3$+DMSO-d_6) 119.35 (C2+C6, Ph), 124.05 (C4, Ph), 128.87 (C3+C5, Ph), 137.75 (C1, Ph), 154.05 (C═O)] and 4-nitrophenylaceto[^{13}C]nitrile [off-white crystals, 0.21 g, 36%; mp 110°C (MeOH), lit.26 mp of the non-labelled analog 115–116°C; HRMS, found M$^{\cdot+}$ 163.0460 $C_7{}^{13}CH_6N_2O_2$ requires 163.0463; ν_{max} (cm^{-1}) (KBr) 2220 (^{13}C≡N), 1520 vs+1350 vs (NO_2); δ_H ($CDCl_3$) 3.89 (2H, d, $^2J_{C,H}$=10.8 Hz, $CH_2{}^{13}CN$), 7.55+8.26 (2×2H, AA′BB′, J_O=8.6 Hz, PNP); δ_C ($CDCl_3$) 23.60 (d, $^1J_{C,C}$=59.5 Hz, *C*$H_2{}^{13}CN$), 116.40 (^{13}CN), 124.39 (C3+C5, PNP), 128.97 (d, $^3J_{C,C}$=3.8 Hz, C2+C6, PNP), 137.00 (d, $^2J_{C,C}$=3.0 Hz, C1, PNP), 147.91 (C4, PNP)] which were separated by preparative TLC (Kieselgel $PF_{254+366}$, Merck; hexane–EtOAc, 7:2), and compound **13c** [0.42 g, 39%, brownish yellow amorphous product; HRMS, found M$^{\cdot+}$ 310.0887, $C_{14}{}^{13}CH_{11}N_5O_3$ requires 310.0895; ν_{max} (cm^{-1}) 3600–2300 (NH), 1700 (C═O), 1530 vs+1355 vs (NO_2), in good agreement with the IR spectrum of the non-labelled analog; δ_H (DMSO-d_6) 7.08 (1H, d, $^2J_{C,H}$=8.6 Hz, COCH$^{13}C_{tetrazole}$), 7.52 (2H, m, 3-H+5-H, Ph), 7.64 (1H, m, 4-H, Ph), 7.72+8.24 (2×2H,

AA′BB′, J_O=8.4 Hz, PNP), 8.04 (2H, m, 2-H+6-H, Ph), except for the multiplicity of the 7.08 ppm signal, practically identical with the spectrum of the non-labelled analog;[1] δ_C (DMSO-d_6) 48.99 (d, $^1J_{C,C}$=58.0 Hz, CO*C*H$^{13}C_{tetrazole}$), 124.00 (C3+C5, PNP), 129.12 and 129.18 (C3+C5 and C2+C6, Ph), 130.96 (d, $^3J_{C,C}$=1.5 Hz, C2+C6, PNP), 134.22 (C4, Ph), 134.91 (C1, Ph), l42.63 (d, $^2J_{C,C}$=2.3 Hz, C1, PNP), 147.29 (C4, PNP), 155.43 ($^{13}C_{tetrazole}$), 193.98 (d, $^2J_{C,C}$=2.3 Hz, C═O), except for the multiplicities of the 48.99, 130.96, 142.63 and 193.98 signals, in good agreement with the spectrum of the non-labelled analog[1]].

3.2. Oxidation of compounds 13a–c with lead tetraacetate

The oxidations were carried out as described[1] for the oxidations of the non-labelled analogs of compounds **13a–c**. The following products were obtained.

3.2.1. 1-Phenyl-[3-^{13}C]prop-2-yn-1-one (15a). [65%; mp. 49–50°C, lit. mp of the non-labelled analog 47–48°C[1] and 49–50°C[28]; HRMS, found $M^{\cdot+}$ 131.0448, $C_8{}^{13}CH_6O$ requires 131.0452; ν_{max} (cm^{-1}) (KBr) 3280 (≡^{13}C–H), 2110/2090d (C≡^{13}C), 1650 (C═O), non-labelled analog 3280, 2100, 1650, lit.29 3311, 2109, 1666; δ_H ($CDCl_3$) 3.44 (0.85H, d, $^1J_{C,H}$=255.3 Hz, ≡^{13}CH). 3.44 (0.15H, s, ≡^{12}CH), 7.50 (2H, m, 3-H+5-H, Ph), 7.63 (1H, m, 4-H, Ph), 8.17 (2H, m, 2-H+6-H, Ph); except for the doublet at 3.44 ppm and the intensity of the singlet at 3.44 ppm, identical with the spectrum of the non-labelled analog;[1] δ_C ($CDCl_3$) 80.77 (≡^{13}CH), 128.69 (C3+C5, Ph), 129.70 (C2+C6, Ph), 134.51 (C4, Ph), 136.17 (C1, Ph), 177.39 (d, $^2J_{C,C}$=13.0 Hz, C═O); due to the high intensity of the 80.77 ppm signal and the presence of spinning side bands, the low intensity CO*C*≡^{13}C signal (which appears at 80.30 ppm in the spectrum of the non-labelled analog[1]) could not be identified; except for the multiplicity of the 177.39 ppm signal, the spectrum is identical with that of the non-labelled analog[1]] from compound **13a** (244 mg, 1.28 mmol).

3.2.2. 3-[(4-Methoxyphenyl)-1-phenyl-[3-^{13}*C*-(15b) and -[2-^{13}C]prop-2-yn-1-one (16b). As a ca 1:1 mixture [72%, mp. 79°C, lit. mp of the non-labelled analog 81–85°C[1] and 81–82°C;[30] HRMS found $M^{\cdot+}$ 237.0865, $C_{15}{}^{13}CH_{12}O_2$ requires 237.0871; ν_{max} (cm^{-1}) (KBr) 2200 (^{13}C≡C), 1670 (C═O), non-labelled analog[1] 2225, 1695 and (in CCl_4 solution)[30] 2196, 1645; δ_H ($CDCl_3$), 3.85 (3H, s, OMe), 6.93+7.64 (2×2H, 2×m, J_O=8.8 Hz, PMP), 7.51 (2H, m, 3-H+5-H, Ph), 7.61 (1H, m, 4-H, Ph), 8.21 (2H, m, 2-H+6-H, Ph), identical for both components of the mixture and with the spectrum[1] of the non-labelled analog; δ_C ($CDCl_3$), *compound* **15b**: 55.43 (OMe), 86.89 (d, $^1J_{C,C}$=173.6 Hz, CO*C*≡^{13}C), 94.30 (COC≡^{13}*C*), 111.92 (d, $^1J_{C,C}$=90.8 Hz, C1, PMP), 114.44 (d, $^3J_{C,C}$=6.1 Hz, C3+C5, PMP), 128.56 (C3+C5, Ph), 129.47 (C2+C6, Ph), 133.88 (C4, Ph), 135.13 (d, $^2J_{C,C}$=2.7 Hz, C2+C6, PMP), 137.09 (d, $^3J_{C,C}$=2.3 Hz, C1, Ph), 161.76 (C4, PMP), 178.00 (d, $^2J_{C,C}$=13.4 Hz, C═O); *compound* **16b**: 55.43 (OMe), 86.89 (CO^{13}*C*≡C), 94.30 (d, $^1J_{C,C}$= 173.6 Hz, CO^{13}C≡*C*), 111.91 (d, $^2J_{C,C}$=12.2 Hz, C1, PMP), 114.44 (C3+C5, PMP), 128.56 (C3+C5, Ph), 129.47 (C2+C6, Ph), 133.88 (C4, Ph), 135.13 (d, $^3J_{C,C}$=2.7 Hz, C2+C6, PMP), 137.09 (d, $^2J_{C,C}$=19.1 Hz, C1, Ph), 161.76 (C4, PMP), 178.00 (d, $^1J_{C,C}$=91.9 Hz, C═O)] from compound **13b** (2.95 g, 1.1 mmol).

3.2.3. 3-(4-Nitrophenyl)-1-phenyl-[2-^{13}C]prop-2-yn-1-one (16c). [43%, pale yellow crystals, mp 150–151°C, lit. mp of the non labelled analog 152–154°C[1] and 148–148.5°C;[30] HRMS, found $M^{\cdot+}$ 252.0611, $C_{14}{}^{13}CH_9NO_3$ requires 252.0616; ν_{max} (cm^{-1}) (KBr) 2185 (^{13}C≡C), 1650 (C═O), 1540 vs+1350 vs (NO_2), non-labelled analog, lit. 2225, 1650, 1540 vs+1335 vs[1] and (in CCl_4 solution) 2207, 1653;[30] δ_H ($CDCl_3$) 7.55 (2H, m, 3-H+5-H, Ph), 7.67 (1H, m, 4-H, Ph), 7.84+8.29 (2×2H, AA′BB′, J_O=8.6 Hz, PNP), 8.20 (2H, m, 2-H+6-H, Ph), identical with the spectrum[1] of the non-labelled analog; δ_C ($CDCl_3$), 89.88 (CO^{13}*C*≡C), 123.85 (C3+C5, PNP), 126.81 (d, $^2J_{C,C}$=11.4 Hz, C1, PNP), 128.84 (C3+C5, Ph), 129.65 (C2+C6, Ph), 133.67 (d, $^3J_{C,C}$=3.0 Hz, C2+C6, PNP), 134.67 (C4, Ph), 136.42 (d, $^2J_{C,C}$=19.1 Hz, C1, Ph), 148.57 (C4, PNP), 177.36 (d, $^1J_{C,C}$=90.0 Hz, C═O); due to the high intensity of the 89.88 ppm signal, the low intensity CO^{13}C≡*C* signal (which appears at 89.18 ppm in the spectrum of the non-labelled analog[1]) could not be identified; except for the multiplicities of the 126.81, 133.67, 136.42 and the 177.36 ppm signals, the spectrum is identical with that of the non-labelled analog[1]] from compound **13c** (0.30 g, 0.97 mmol).

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