Review

Genesis of rare molecules using light-induced reactions of matrix-isolated tetrazoles

L.M.T. Frija, M.L.S. Cristiano, A. Gómez-Zavaglia, I. Reva, R. Fausto

A Research Institute for Medicines and Pharmaceutical Sciences (iMed.UL), Faculty of Pharmacy, University of Lisbon, Av. Prof. Gama Pinto, 1649-003 Lisbon, Portugal
b CCMAR and Department of Chemistry and Pharmacy, F.C.T., University of Algarve, Campus de Gambelas, 8005-039 Faro, Portugal
c Department of Chemistry, University of Coimbra, 3004-535, Portugal
d Centro de Investigación y Desarrollo en Crioterapia de Alimentos (Conicet La Plata, UNLP), RA-1900, Argentina

A R T I C L E  I N F O

Article history:
Received 8 June 2013
Received in revised form 6 September 2013
Accepted 20 September 2013
Available online 1 October 2013

Keywords:
Tetrazole
Photochemistry
Matrix-isolation
Rare molecules
IR spectroscopy

A B S T R A C T

Tetrazoles exhibit a very rich photochemistry, strongly influenced by the nature of substituents in the tetrazolic ring. Photolysis of representative tetrazoles trapped in a rigid environment of solidified noble gases at cryogenic temperatures (usually argon at 10–15 K) results in photofragmentation of the monomeric species with a wide range of exit channels. Since the obtained fragments are generally confined to the matrix cage where they are formed, no subsequent cross-reactions involving species resulting from photolysis can occur, strongly reducing the number of possible photoproducts in comparison with gas phase or solution studies. These conditions introduce a useful simplification for the interpretation of the reaction mechanisms and enable spectroscopic characterization of novel and/or highly reactive molecules. In this review, we provide an updated report on the photolysis of matrix-isolated tetrazoles, focusing on the scope and usefulness of this methodology for generation of rare molecules and investigation of photodissociation pathways. Special emphasis is placed on mechanistic interpretations and characterization of rare molecules and on the relevance of conformation and tautomerism on the photochemistry of the studied compounds.

© 2013 Elsevier B.V. All rights reserved.

C O N T E N T S

1. Introduction .......................................................................................................................... 72
2. Photochemistry of matrix-isolated tetrazoles: an effective tool to generate and characterize rare molecules .............................................................................................................. 73
  2.1. Unsubstituted tetrazole ........................................................................................................ 73
  2.2. 1-(Tetrazol-5-yl)ethanol (TE) ........................................................................................... 73
  2.3. 5-Methoxy-1-phenyl-1H-tetrazole (5MPT) ...................................................................... 74
  2.4. 5-Ethoxy-1-phenyl-1H-tetrazole (5EPT) .......................................................................... 75
  2.5. 2-Methyl-2H-tetrazol-5-amine (2MTA) .......................................................................... 76
  2.6. 5-Mercapto-1-methyltetrazole (MMT) ............................................................................ 77
  2.7. 1-Phenyl-tetrazolone (PT) ................................................................................................ 79
  2.8. 1-Phenyl-4-allyltetrazolone (APT) .................................................................................. 80
  2.9. 1-Alllyltetrazole (1-ALT) and 2-allyltetrazole (2-ALT) ....................................................... 81
  2.10. Tetrazole coupled with another heterocycle .................................................................... 81
  2.10.1. 5-[1H-tetrazol-1-yl]-1,2,4-triazole (T) ......................................................................... 83
  2.10.2. 2-[Tetrazol-1-yl]pyridine (Py2T), 3-[tetrazol-1-yl]pyridine (Py3T) and 2-[tetrazol-5-yl]pyridine (PyT) ......................................................................................................................... 84
  2.10.3. 2-[1H-tetrazol-5-yl]ethyl]-1,2-benzothiazol-3(2H)-one 1,1-dioxide (1-TE-BZT) ........... 85
3. Conclusions .......................................................................................................................... 89
4. Acknowledgements ............................................................................................................. 89
5. References .......................................................................................................................... 89

* Corresponding author. Fax: +351 21 7946476.
E-mail address: llfriga@ff.ulis.pt (L.M.T. Frija).

1389-5567/$20.00 © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.jphotochemrev.2013.09.001
1. Introduction

The chemistry of tetrazole and its derivatives remains a topic of intense research. The wide interest in this class of compounds stems mainly from their potential and important applications in major areas such as medicine [1], agriculture [2], automobile industry [3], imaging technology [4], coordination chemistry [5] and as high energy materials [6]. In drug design and development, 5-substituted tetrazoles are mostly used as a bioisosteric replacement for the carboxylic acid moiety [1] and the 1,5-disubstituted tetrazole ring is known as an excellent mimic for the cis-amide bond [7].

Tetrazoles are also interesting molecules from a structural point of view. Hydrogen atoms directly bound to the tetrazole ring are labile and may give rise to different tautomers, their relative populations depending on the chemical environment. Unsubstituted tetrazole (CN₄H₂) occurs exclusively as the 1H-tautomer in the crystalline phase and mostly as the 2H-tautomer in the gas phase (~90% of the total population at 90 °C). In solution, both tautomers coexist, with the population of the most polar 1H-form increasing with the polarity of the solvent [8–12]. The infrared spectrum of tetrazole (CN₄H₂) isolated in solid argon (T= 10 K) was investigated in one of our previous studies, showing essentially the expected signature of the 2H-tetrazole tautomer [13]. The amount of the 1H-tautomer in the matrix was found to be ca. 10% of that of the most abundant form. This study has solved a long-term controversy regarding the existence of the 1H-tautomer of tetrazole in the gas phase [13–16]. In the case of substituted tetrazoles, tautomerism may also involve substituent groups, as was found, for instance, in the case of 1-methyl-tetrazol-5-thione and 2-methyl-tetrazol-5-amine [17,18].

The photoactivity of tetrazoles has been widely investigated, in solution and in the rigid environment of solid matrices, resulting in a wealth of information that unraveled the potential of tetrazoles as precursors of a wide variety of new scaffolds through photolysis [17–27]. The major factor contributing to the observed range and versatility in photochemical pathways for tetrazoles is the possibility of tautomerism. In general, the presence of labile hydrogen atoms (either directly linked to the tetrazole ring or belonging to the tetrazole substituents) is a source of complexity in photochemical reactions, generally opening additional primary channels or enabling secondary photochemical reactions, concomitantly with the dominant primary photoprocesses, and thus interfering with selectivity and product control [17–19,27–30].

When substituents are linked to the tetrazole ring, the photochemistry of the molecule can also be influenced by their nature and conformational flexibility, which may favor or exclude certain reaction channels, determining the nature and relative amount of the final photoproducts [17,23].

The photochemistry of tetrazoles in solution has been reviewed recently [31]. However, regarding the photochemistry of matrix-isolated tetrazoles, a wide range of information is available but data are dispersed, prompting the need for a comprehensive review.

Matrix isolation is a technique where gaseous atoms or molecules are commonly trapped in an environment of solidified noble gases at temperatures close to absolute zero (matrices can also be built from other gases; essentially inert, like N₂, or even reactive like O₂, for instance) [32–36]. Under these conditions, intramolecular rearrangements are inhibited for any process with an activation barrier larger than a few kJ mol⁻¹. In addition, because the matrix rigidity prevents diffusion of the sample, in general bimolecular reactions are also suppressed. In the matrix, the lifetime of unstable or usually short-lived species can then be increased allowing for detailed structural investigations using conventional spectroscopic techniques [32].
A further advantage of this methodology is that the technique of detection can easily be adapted to the problem under investigation, due to the spectroscopic transparency of the host gas. Vibrational spectroscopy, in particular, becomes a very powerful tool for studies of the structure and reactivity of moderate-size organic molecules (up to 30–35 atoms) when combined with low temperature matrix isolation. Infrared spectroscopy provides direct data on frequencies and intensities of characteristic absorptions of the isolated species, and matrix isolation facilitates obtaining this information, due to the high resolution of infrared matrix spectra and high sensitivity of the method. In the spectra of matrix-isolated compounds, the effect of inhomogeneous band broadening nearly vanishes in comparison with the condensed phase and, unlike for the gaseous state, the fine rotational structure is, in general, completely absent. Besides, unlike for solutions, the effect of the environment on the structure of the molecules under investigation is generally negligible. These factors result in a unique narrowing of bands in vibrational spectra (down to a few tenths of cm⁻¹), which makes possible to detect band shifts of a few wavenumbers that are characteristic for the finest changes of sample’s structure. Moreover, because the inert matrix most of times only slightly affects the structure of the isolated molecules it is possible to compare directly matrix experimental results and theoretically calculated spectra, which are commonly obtained for the single molecule in vacuo.

One of the most important advantages of matrix isolation spectroscopy is the possibility of following photochemical reactions unambiguously. For a matrix isolated compound, in situ photolysis enables selective introduction of energy in the molecule under study, controlling the range of possible rearrangements of the isolated species. Thus, a wide range of intramolecular changes, up to molecule decomposition and formation of new entities, can be studied. In addition, contrary to what occurs in the gas phase or in solution, where a multitude of possible photochemical reaction pathways leading to different products can be observed, in a matrix the processes are cage-confined (molecular diffusion is inhibited), and therefore a useful simplification to the photochemical reactivity is obtained. For instance, if photofragmentation of a matrix-isolated species occurs, the obtained fragments generally stay in the matrix cage where they are produced. Then, no subsequent cross-reactions involving species resulting from photolysis of different reactant molecules can occur, reducing the number of possible photoproducts in comparison with gas phase or solution studies and thereby facilitating the interpretation of reaction mechanisms.

The matrix-isolation technique, coupled with infrared spectroscopy, has been used for many years to study the photochemistry of several families of molecules with biological or industrial relevance. Among them, tetrazoles have been considered in great detail. The photochemistry of matrix-isolated unsubstituted tetrazole was studied for the first time by Maier et al. [19]. Our recent studies on tetrazole derivatives provided a general pattern of reactivity for this family upon UV irradiation [17,18,22–27]. Besides, the observation of a number of relatively unusual or highly reactive molecules, formed from photolysis of the studied tetrazoles, such as antiaromatic azirines, azides, isocyanates or isothiocyanates, the matrix-isolation approach led, in some cases, to the first spectroscopic characterization of some of these species.

In the following sections of this review, an overview of the photochemistry of matrix-isolated tetrazoles is presented. Special emphasis is put on the potential and interest of this class of compounds as starting materials for light-induced formation of rare chemical species, and on the relevance of conformation and tautomerism for the photochemical reactivity of the studied compounds.

2. Photochemistry of matrix-isolated tetrazoles: an effective tool to generate and characterize rare molecules

2.1. Unsubstituted tetrazole

The photochemistry of matrix-isolated unsubstituted tetrazole was studied for the first time by Maier et al. [19]. Upon photolysis with the 193 nm emission line of an ArF laser, rapid photolysis of tetrazole was observed, leading to extrusion of N₂ and formation of several different photoproducts, including nitrilime, carbodiimide, diazomethane, an NCH···NH complex and cyanamide (Scheme 1) [19]. The use of different excitation wavelengths, allowed the accumulation of cyanamide and carbodiimide as final products. That study also delivered the first vibrational signature of matrix-isolated nitrilime [19].

2.2. 1-(Tetrazol-5-yl)ethanol (TE)

Recently, 1-(tetrazol-5-yl)ethanol (TE) has assumed an important role in the synthesis of tetrazole-saccharinate-type nitrogen ligands [37]. Our recent matrix isolation study of TE allowed a detailed investigation of the structure of the compound [26]. Furthermore, it appears as a representative example of the power of this technique in the investigation of tautomer-selective photochemistry. Indeed, 1-(tetrazol-5-yl)ethanol presents two different tautomeric forms, which are stabilized by different types of intramolecular hydrogen bonds (NH···O or OH···N) (Fig. 1).

Remarkably, these non-covalent interactions were found to be relevant to the different photochemical behavior of the tautomers in an argon matrix.

Both 1H and 2H tautomers can give rise to different conformational isomers. In the case of tautomer 1H, the low barriers separating different conformers allow only the observation of the most stable form, since the higher energy forms convert into the most stable one during deposition of the matrix (this phenomenon is known as

![Scheme 1. Photodecomposition of matrix-isolated unsubstituted tetrazole.](image-url)
conformational cooling and has been studied in detail in our laboratory [38–42]. Thus, at 30 K, only two species can be isolated in a solid argon matrix: the most stable forms of 1H and 2H tautomers. This allowed the observation of a tautomer selective photochemistry, with the 2H-tautomeric form undergoing prompt unimolecular decomposition upon irradiation at $\lambda > 200$ nm to produce azide and 2-hydroxypropanenitrile, while the 1H-tautomer remained photostable (Scheme 2). For the 1H-tautomer, photo-induced ring-cleavage requires simultaneous cleavage of the intramolecular H-bond connecting the tetrazole hydrogen to the oxygen atom of the substituent (Scheme 2), which appears to preclude the reaction. In the case of 2H tautomer there are low energy conformers that can be easily accessed from the lowest energy conformer in which cleavage of the intramolecular H-bond is not required during the ring-opening reaction. In this case, the ring-opening reaction is then much easier, since the two molecular fragments resulting primarily from the reaction are not linked by any H-bond (Scheme 2).

2.3. 5-Methoxy-1-phenyl-1H-tetrazole (5MPT)

Upon UV irradiation ($\lambda > 235$ nm), 5MPT was found to react through two fragmentation pathways (see Scheme 3): (a) $N_2$ elimination, with production of the antiaromatic 3-methoxy-1-phenyl-1H-diazirine (MPD), which was observed experimentally for the first time during our studies [23] and (b) ring-opening, leading to phenylazide and methylcyanate. The latter compound was found to quickly convert to its more stable isomer methyl-isocyanate, in keeping with previous studies [43–46]. Phenylazide further eliminated molecular nitrogen to give phenylisocyanate that underwent subsequent ring expansion to
form the seven-membered ring 1-aza-1,2,4,6-cycloheptatetraene (ACHT), which is unambiguously identified by the observation of its characteristic IR band at ca. 1913 cm\(^{-1}\) (Fig. 2). Identification of phenylazide was straightforward, since the vibrational spectrum of matrix-isolated phenylazide is well-known [28,47,48].

In 5MPT, both observed photoprocesses involve the cleavage of the \((N-3)-(N-4)\) bond. In channel a (Scheme 3), the cleavage of the \((N-1)-(N-2)\) bond occurs in addition. Channel b, which was found to correspond to the preferred reaction channel [23], also implies disruption of the \((C-5)-(N-1)\) bond (Scheme 3). According to DFT(B3LYP)/6−311++G(d,p) calculations performed on 5MPT, these are the three longest bonds in the tetrazole ring (calculated lengths are longer than 135.5 pm) [23]. In turn, the \((N-2)-(N-3)\) and \((C-5)-(N-4)\) bonds were calculated to be considerably shorter (128.0 and 131.3 pm, respectively). Hence, the bonds that are clef in the photochemical reactions correspond to the weaker bonds which are formally single bonds.

2.4. 5-Ethoxy-1-phenyl-1\textit{H}-tetrazole (5EPT)

5-Ethoxy-1-phenyl-1\textit{H}-tetrazole (5EPT) differs from 5MPT in the length of the alkyl substituent. The photochemistry of these two molecules was expected to be similar but the increased conformational flexibility brought by the ethoxy group of 5EPT appeared as a source of complexity in the analysis of the experimental data. Indeed, 5EPT possesses 3 conformational isomers, which were predicted by DFT(B3LYP)/6−311++G(d,p) calculations [25] to have relative energies within the 0−3 kJ mol\(^{-1}\) range and, then, are all significantly populated in the gas phase prior to deposition. Fortunately, these conformers are separated by low energy barriers (less than 4 kJ mol\(^{-1}\)) on the ground-state potential energy surface and, during deposition of the matrix, the higher energy forms relax to the most stable conformer. Hence, only the most stable conformer of 5EPT remains trapped in the as-deposited matrix. This conformer has the ethyl group placed nearly in the plane of the tetrazole ring and as far away as possible from the phenyl group. The dihedral angle between the two rings (phenyl and tetrazole) was calculated to be ca. 30° [25].

UV irradiation (\(\lambda > 235\) nm) of matrix-isolated 5EPT gives rise to different primary photochemical reactions, which are equivalent to those observed for 5MPT: (a) \(N_2\) elimination, leading to production of the anti-aromatic 3-ethoxy-1-phenyl-1\textit{H}-diazirine (EPD), a photoproduct observed and spectroscopically characterized for the first time [25] and (b) tetrazole ring-opening, leading to ethylvanazide and phenylazide (as found for the experiments on 5MPT, phenylazide was also shown to subsequently release \(N_2\), forming phenyl nitrene that later rearranges to ACHT). Like in the case of 5MPT, only formally single bonds are clef in the photoinduced reactions of 5EPT and the pathway leading to ethylvanazide and phenylazide prevails.

The photoproducts diazirine and ethylvanazide possess more than one low energy conformational state but, in the photoyslates matrix, were both observed to exist in a single conformation (the trans isomer, where the C−O−C−C dihedral is ca. 180°; see Fig. 3). Ethylvanazide has one intramolecular degree of freedom, corresponding to the internal rotation around the central (NC)O−C\(_2\)H\(_5\) bond, which may result in the existence of different conformers (trans and gauche). However, DFT(B3LYP)/6−311++G(d,p) calculations indicate that the energy barriers separating the less stable gauche conformers from the conformational ground state are very low (less than 4 kJ mol\(^{-1}\) [25]). Then, similarly to the matrix-isolated reactant (5EPT), the photochemically obtained ethylvanazide can also undergo conformational cooling upon its production, justifying the sole observation in the irradiated matrices of the most stable trans conformer. Three conformers separated by low intramolecular energy barriers (less than 3 kJ mol\(^{-1}\)) were also predicted by the DFT(B3LYP)/6−311++G(d,p) calculations for EPD. Again, conformational cooling leads to exclusive observation.

**Fig. 2.** Bottom: Changes in infrared spectrum of 5MPT trapped in an argon matrix induced by UV (\(\lambda > 235\) nm) irradiation (spectrum of UV-irradiated (80 min) sample minus spectrum of freshly deposited matrix). Upper frames: B3LYP/6−311++G(d,p) calculated spectra of the observed photoproducts. In the theoretical spectra, intensities were scaled by different factors, in order to better simulate the experimental spectrum presented in the figure. Reproduced from [23] with permission.
of the most stable conformer in the SEPT photolyzed matrix. One shall point out that these results demonstrate convincingly that, after their photochemical generation in a low temperature matrix, molecules may undergo efficient conformational cooling to their most stable conformers, since energy dissipation upon returning to the ground state leads to local heating of the matrix, thus facilitating conformational relaxation.

It is also interesting to mention that ethylcyanate is known to isomerize readily at room or higher temperatures to ethylisocyanate [49], and the process is believed to be autocatalyzed [49, 50]. Because of its instability, ethylcyanate can only be stored at low temperature and its application in chemical reactions requires its generation in situ prior to use [49–52]. For the same reason, this compound had not been the subject of previous detailed experimental structural or vibrational studies and was only characterized in some detail in our investigation [25]. No evidence of isomerization of ethylcyanate to ethylisocyanate was found in our study, indicating that, under matrix-isolation conditions (at temperatures of ~15 K) ethylcyanate is thermally stable and also photostable (λ > 235 nm).

The detailed investigation of the photochemistry of matrix-isolated 5-alkoxytetrazoles (5MPT and SEPT) [23, 25] was instrumental for the interpretation of photochemical pathways of other tetrazole derivatives that exhibit much more complex patterns of photoreactivity, for instance in cases where substitution enables tautomerism involving the tetrazole ring, as described below [18, 22, 24].

2.5. 2-Methyl-2H-tetrazol-5-amine (2MTA)

When the substituent at the tetrazole ring carbon atom is an amino or imino group, photolysis can result in production of small C-, N- and H-containing molecules of important astrophysical and/or industrial interest (e.g., CN₂H₃, CN₃H or CNH₃ isomers). Thus, investigation of the photochemistry of 2-methyl-2H-tetrazol-5-amine (2MTA) was especially challenging. To avoid the increased complexity introduced by the presence of a labile hydrogen atom at the tetrazole ring, 2-methyl-2H-tetrazol-5-amine (2MTA) was selected as a simple prototype molecule having the adequate characteristics for studying the photochemistry of amino/imino containing tetrazoles and their photoproducts as well as their structural and vibrational properties.

2MTA may exist in different tautomeric forms (Fig. 4). The possibility of hydrogen shift from the amino group to three different positions of the tetrazole ring leads to three possible pairs of tautomers bearing an imine (or amine) NH substituent at the position 5 [17]. Taking as reference the atom numbering of the tetrazole ring in 2MTA, the hydrogen involved in the tautomeric rearrangement can occupy positions 1, 3 and 4 of the ring. In the first case tautomerism leads to the imine species, 2-methyl-1,2-dihydro-5H-tetrazol-5-imine (structures C in Fig. 4), which can exist in two different conformations, depending on the orientation of the hydrogen atom in the imino group at position 5 [17]. The remaining two cases lead to mesoionic-type structures.

![Fig. 3](image1)

Fig. 3. (A) DFT(B3LYP)/6–311++G(d,p) calculated spectra of the observed photoproducts of SEPT (scaled with a uniform factor of 0.978). (B) Extracted spectrum of the photoproducts formed after 60 min of UV-irradiation (λ > 235 nm) of SEPT trapped in an Ar matrix. The extracted spectrum was obtained by subtraction of the scaled spectrum of non-irradiated matrix from the spectrum of irradiated sample. The scaling factor was chosen so that the absorptions due to the originally deposited compound (SEPT) were nullified.

Adapted from [25] with permission.

![Fig. 4](image2)

Fig. 4. Structures of 2-methyl-2H-tetrazol-5-amine (A) and of its imine (aminide) tautomers: 3-methyl-1H-tetrazol-3-ium-5-amine (B), 2-methyl-1,2-dihydro-5H-tetrazol-5-imine (C) and 2-methyl-3H-tetrazol-2-ium-5-amine (D). In the case of the amine tautomers, the placements of the charges on atoms correspond to one of the possible canonical forms for the mesoionic structures, which were also used to name the compound.
2-methyl-3H-tetrazol-2-iium-5-amine (Fig. 4, structure D) and 3-methyl-1H-tetrazol-3-iium-5-amine (Fig. 4, structure B), respectively, that may also exist in two different stable conformations [17].

The experimental spectrum of 2MTA isolated in an argon matrix fits well the spectrum of tautomer A calculated at the DFT(B3LYP)/6-311++G(d,p) level of theory and no evidence of presence of any of the imine (amine) tautomers was found. This observation is in agreement with the theoretically predicted relative energies of tautomers B, C, D: all of them are less stable than tautomer A by more than 100 kJ mol⁻¹ and are not populated in the gas phase [17].

In situ UV irradiation (λ > 235 nm) of matrix-isolated 2MTA induces three main primary photochemical processes. Two of them correspond to the prototype reactions found for other tetrazoles, viz., (a) N₂ elimination, with production of 1-methyl-1H-diazirine-3-amine, and (b) ring cleavage leading to production of methyl azide and cyanamide. The third observed reaction [pathway (c); Scheme 4] was taumORIZATION of 2MTA to mesionic 3-methyl-1H-tetrazol-3-iium-5-amine (tautomer B, Fig. 4) via [1,3]-hydrogen shift.

The photoproduced amine tautomer B(I) is the lowest energy imine/amine tautomer of 2MTA and, among the six possible imine/amine tautomers it is one of the two forms that can be directly produced from 2MTA as a result of an energetically accessible hydrogen-shift (see Fig. 4). The other is conformer C(II) of 2-methyl-1,2-dihydro-5H-tetrazol-5-imine, which was not identified as contributing to the spectra of the irradiated matrix (this form is less stable than B(I) by ca. 20 kJ mol⁻¹ and has a non-planar structure, then requiring a more important rearrangement of the matrix to be produced from 2MTA [17]). Once formed, the photo-produced amine form stays in the matrix, since it can be comparatively less photoreactive than 2MTA because the two pathways similar to (a) and (b) would require an additional hydrogen atom migration.

Following the primary photo rearrangements, secondary reactions were observed, leading to spectroscopic identification of methylenimine and hydrogen isocyanide (CNH) [17]. As it can be easily recognized in Scheme 4, these secondary reactions were also facilitated by the presence of labile hydrogen atoms in the primary photoproducts.

2.6. 5-Mercapto-1-methyltetrazole (MTT)

As observed for the 2MTA molecule, tautomeration was expected to be relevant in 5-mercapto-1-methyltetrazole (1-methyl-1H-tetrazole-5-thiol; MTT). In this case, tautomeration may be seen as mainly determined by the possibility of the sulphur atom bound to C-5 to adopt the thione or the thiol form (Fig. 5).

The 5-mercapto tautomer D (1-methyl-1H-tetrazol-5-thiol) may adopt two different conformers, I and II. Form I, where the methyl group and sulhydryl hydrogen atom are oriented to opposite sides, is more stable [18]. There are also two 5-thione tautomers, which differ in the position of the tetrazole-ring hydrogen atom (see Fig. 5). The most stable thione tautomer A (1-methyl-1,4-dihydro-5H-tetrazol-5-thione) corresponds to the global minimum
of the molecule in the gas phase and is considerably more stable than all other species [thiol tautomer D-I is the second most stable form and has a relative energy of 32.5 kJ mol\(^{-1}\), calculated at the DFT(B3LYP)/6–311++G(d,p)] [18].

As expected from the predicted relative stability of all the possible tautomers of MTT, only the most stable form (1-methyl-1,4-dihydro-5H-tetrazol-5-thione) was found in the as-deposited argon matrices. This was clearly demonstrated by the pretty good agreement between the observed infrared spectrum of the as-deposited argon matrix of MTT and that calculated at the DFT[B3LYP]/6–311++G(d,p) level of theory for thione tautomer A [18].

Scheme 5 depicts the proposed reaction pathways for the observed photochemistry of MTT upon irradiation at \(\lambda > 235\) nm. In general terms, the observed photochemistry of MTT follows closely those observed for other tetrazoles, in particular 2MTA [17] and 1-phenyl-tetrazolone [18]. Nevertheless, the presence of the sulphur atom in the molecule opens additional reaction pathways. Indeed, in MTT molecular nitrogen can be eliminated by two different ways in a primary photolytic step: (a) alone, with simultaneous production of 1-methyl-1H-diazirine-3-thiol (MDT, which is produced in two different conformers), and (b) together with atomic sulphur, leading to production of N-methyl-carbodiimide. Pathway (a) is similar to the reaction of 2MTA leading to formation of 1-methyl-1H-diazirine-3-amine (see Scheme 4), whereas pathway (b) has no counterpart in the photochemistry of MTT. In addition to the above reactions, MTT can also undergo (c) ring cleavage leading to production of methyl isothiocyanate and azide and (d) elimination of carbon monosulphide leading to production of 1-methyl-1,2-tetrazate (which then eliminates \(N_2\) to form methyl diazene) [18].

Another pathway can also be postulated, involving cleavage of the (C-5)-(N-1) and (N-3)-(N-4) bonds and leading to methyl azide and HNCS, in a similar way to what succeeds for 2MTA. However, despite this pathway could not be discarded in a definitive way, no clear experimental evidence of its occurrence in the present case could be found.

Fig. 6 shows the spectra of matrix-isolated MTT before and after irradiation, in the 2300–1500 cm\(^{-1}\) region, where characteristic bands of the photoproducts were observed [18] as well as the calculated spectra of the photoproducts in the same spectral region. The dependence of the experimental spectra on the time of irradiation clearly reveals two types of variation patterns of band intensities: some bands increase in intensity mostly during the first 20 min of irradiation and decrease upon prolonged irradiation (group A bands, 1850–1700 cm\(^{-1}\) range), while intensity of other bands (group B, 2250–2050 cm\(^{-1}\) range) increases during the whole time of irradiation. Observation of bands of type A clearly indicates that there are primary photoproducts, which undergo secondary reactions. These bands were identified as belonging to 1-methyl-1H-diazirine conformers, which undergo secondary photolysis to methyl diazene (with elimination of CS; see Scheme 5). Bands of type B are due to the other photoproducts and were assigned based on results of theoretical calculations of the infrared spectra of the postulated reaction products [18].

It is interesting to note that MTT is a rather reactive tetrazole, under the experimental conditions used, when submitted to UV irradiation (\(\lambda > 235\) nm). In fact, the bands due to MTT reduce to ca. 60% of their initial intensity after the first 20 min of irradiation and to less than 1% after 100 min of irradiation, i.e., MTT almost totally converts into other species after 100 min of irradiation. It is also worth mentioning that at the end of the irradiation process, the total intensity of the spectrum was found to be considerably weaker (less than 30% of the initial total absorbance) than that of the as-deposited matrix. This result clearly demonstrates that some of the final products absorb only weakly in the infrared or do not absorb at all (among them, \(N_2\) and S are certainly the dominant species; see Scheme 5). The high observed photoactivity is in keeping with the widespread usage of tetrazole thiones in imaging systems, namely as stabilizers in photography [53], as deep-UV resists
in photolithographic applications [54] and as photoresponsive capping agents in the semiconductor photocatalytic industry [55].

2.7. 1-Phenyl-tetrazolone (PT)

1-Phenyl-tetrazolone (PT) is another tetrazole derivative showing tautomerism. It can exist in five tautomeric forms: two keto tautomers, one mesionic alate form and two hydroxy conformers (Fig. 7). 1-Phenyl-1,4-dihydro-5H-tetrazol-5-one (keto tautomer “A” in Fig. 7) was predicted to be considerably more stable than all the remaining species, due to the existence in this tautomer of more favorable interactions between the phenyl hydrogen atoms ortho to the tetrazole ring and the N-2 and carboxyl oxygen atoms [22]. Because of the much greater stability of the “A” tautomer of PT, this is the only species populated in the gas phase at room temperature. Then, tautomer “A” is the unique species initially present in the matrix-isolated PT. This fact strongly simplifies the subsequent photochemical experiments and interpretation of the results.

Compared to 5MPT and 5EPT, the photochemistry of 1-phenyl-tetrazolone (PT) is rather complex. The main observed photoreactions induced by UV light (λ > 235 nm) in matrix-isolated PT are summarized in Scheme 6. They are: (a) extrusion of molecular nitrogen, giving 1-phenyl-diaziridin-3-one; (b) elimination of HNCO with production of phenylazide; (c) tetrazole ring-opening, leading to phenylisocyanate and azide; and (d) loss of CO, leading to the final production of phenylidazene and N₂, with all probability occurring via the phenyltetrazete intermediate.

Pathway a, leading to the production of 1-phenyl-diaziridin-3-one, is similar to pathway a in 5MPT and 5EPT. The photoproduced diaziridinone adopts two different conformers, which were characterized for the first time in our study [22]. Theoretical calculations indicated that the conformer where the phenyl group and the diaziridinone-ring hydrogen atom are trans to each other is more stable by 14.5 kJ mol⁻¹ than the one where these groups are cis to each other. The most intense bands of the diaziridinone isomers correspond to the νC=O and νC=N antisymmetric stretching vibrations and one of the phenyl ring out-of-plane bending modes (νC−H ring 1). All the bands corresponding to these vibrations were identified in the IR spectra of the photolyzed matrix [conformer trans: 1931.9/1926.0/1877.8/1874.3 cm⁻¹ (site-split Fermi resonance doublets resulting from interaction of νC=O with the first overtone of νC=N, see Fig. 8), 964.5/962.8 (νC=N) and 771.0 cm⁻¹ (νC−H ring 1); calculated values: 1931.2, 945.5 and 756.2 cm⁻¹; conformer cis: 1913.1/1899.4/1865.8/1862.7 (Fig. 8), 924.0/922.8 and 695.3 cm⁻¹, respectively; calculated values: 1921.2, 910.0 and 694.2 cm⁻¹].

The bands due to the diaziridinone are relatively easy to identify, because their intensity increased only during the first stages of irradiation (i.e., until ca. 30 min of irradiation). Subsequent irradiation led to a decrease of intensity of these bands, which was accompanied by the appearance in the spectra of new bands (and subsequent progressive growth) that could be assigned to secondary photoproducts resulting from photolysis of the diaziridinone. Two different pathways could be postulated for photodegradation of the diaziridinone, the first one yielding phenylidazene (in two different conformers) plus CO, and the second one leading to production of phenylnitrene and isocyanic acid. The phenylnitrene underwent the usual subsequent ring expansion to ACHT [16.47,48,56–58], which gives rise to the characteristic bands observed at 1894.2 and 1889.8 cm⁻¹ [56,57]. These bands grew mostly at later stages of irradiation (see Fig. 8).

Pathway b leads to production of phenylazide and isocyanic acid (HNCO) and is similar to pathway b in 5MPT and 5EPT. The experimental identification of isocyanic acid was complicated because the most intense bands of this compound are nearly coincident with bands due to other photoproducts, in particular phenylisocyanate, which is formed in pathway c and is one of the major observed photoproducts. Nevertheless, bands assigned to HNCO

---

**Fig. 6.** (A) Infrared spectra (2300–1500 cm⁻¹ region) of MTT along the irradiation (λ > 235 nm) process. (B) DFT(B3LYP)/6–311+G(d,p) calculated spectra for MTT and most of the observed photoproducts (among the identified photoproducts, only CS and HN do not absorb in the spectral region shown in the figure). The intensity of the calculated band of MTT was multiplied by 7, in order to approximately preserve the relative band intensities in the experimental and calculated spectra shown in the figure. Adapted from [18] with permission.

**Fig. 7.** Tautomers of 1-phenyltetrazolone (PT); (A) 1-phenyl-1,4-dihydro-5H-tetrazol-5-one; (B) 1-phenyl-1H-tetrazol-3-ium-5-olate; (C) 1-phenyl-1,2-dihydro-5H-tetrazol-5-one; (D) 1-phenyl-1H-tetrazol-5-ol (two conformers, I and II).
were observed at ca. 2263 (buried under the intense group of bands due to νNCO as of phenylisocyanate), 824 and 630 cm⁻¹, in fairly good agreement with the DFT(B3LYP)/6–31+G(d,p) calculated frequencies for this molecule (2287, 850 and 627 cm⁻¹, respectively) [22]. Since the bands assigned to phenylazide still continued to grow considerably after 60 min of irradiation, it was concluded that in this case phenylazide undergoes its usual subsequent reactions (as mentioned before, phenylazide tends to release N₂ and form phenyltrinitrene and then ACHT) only with relatively low efficiency.

Pathway c corresponds to tetrazole ring opening leading to phenylisocyanate and azide (see Scheme 6). No indications were found pointing to additional reactions of these compounds under the experimental conditions used [22]. The experimental spectrum of phenylisocyanate is readily identifiable because it shows a very characteristic intense multiplet in the 2290–2260 cm⁻¹ region (Fig. 8) due to the νNCO antisymmetric stretching vibration that clearly dominates the spectrum of the photolyzed matrix. According to the theoretical predictions, the intensity of such unusually intense band represents about 90% of the total intensity of the spectrum of phenylisocyanate. The bands corresponding to azide could also be identified in the spectra of the irradiated matrix by comparison with the spectrum of the matrix-isolated azide previously reported by Himmel et al. [59].

A fourth possible reaction pathway (pathway d; see Scheme 6) could not be discarded (though it could not be doubtlessly proved in our study [22]). This reaction channel can lead to production of phenyldiazene through initial elimination of CO (to yield phenyltetrazete) followed by N₂ extrusion.

It is interesting to notice here that for 5MPT, 5EPT and PT all the primary photochemical reactions imply simultaneous cleavage of two single bonds in the tetrazole ring of the reactant molecule. Compared to PT, the number of single bonds in both 5MPT and 5EPT tetrazole rings is reduced from 4 to 3, and the number of observed primary photochemical processes decreases from 3 (or 4, depending if pathway d in PT is effectively active or not) to 2. Indeed, as it will be shown in the next sections, this trend appears to be a general rule for tetrazole derivatives.

### 2.8. 1-Phenyl-4-allyl-tetrazolone (APT)

The relevance of allyltetrazole derivatives in organic synthesis attaches ever increasing interest to their study. Particularly, the title compound of this subsection is an important precursor of other biologically active heterocycles, through photolysis [60,61], and may be obtained from the corresponding 5-allyloxytetrazoles in quantitative yields through a thermally induced Claisen-type isomerization [62–66]. Furthermore, allyltetrazolones are important structural units of biologically active systems, acting as key intermediates in the biosynthesis of several important biomolecules [67–69].

As can be observed from Fig. 9, the structure of APT differs from that of 1-phenyl-tetrazolone (PT) in the replacement of the hydrogen linked to the tetrazole ring by an allyl group. Thus, one can expect that the observed differences in their photochemistry result essentially from this relevant structural modification. In addition is the increase in conformational freedom brought by the allylic
substituent might also be thought to open the possibility of other exit channels from photolysis.

All minimum energy conformations in APT differ on the orientation of the –CH=CH₂ group on the allylic chain relatively to the tetrazole ring. Three conformers were found on the potential energy surface of the molecule (Fig. 9). In these, the N–CH₂–CH=CH₂ dihedral angle is ca. −123° (Sk’), 121° (Sk) and −2° (Syn) [24] and their relative populations in the gas phase prior to deposition, as predicted by DFT(B3LYP)/6–311++G(d,p) calculations, are 41.8%, 38.8% and 19.4%, respectively [24].

Somewhat surprisingly, we found that the photochemistry exhibited by matrix-isolated APT is not significantly influenced by the conformation of the allyl group. Indeed, matching closely the general scheme for the photochemistry of phenyltetrazolic compounds, the following photolysis pathways were identified for matrix-isolated APT (Scheme 7): (a) N₂ elimination with formation of 1-allyl-2-phenylaziridine-3-one (APD) which partially reacts further to form 1-allyl-1H-benzoimidazol-2(3H)-one (ABZ); (b) ring cleavage to form allyl isocyanate and phenyl azide (and then ACHT) and (c) ring cleavage to form phenylisocyanate and allyl azide. Interestingly, the allylic chain is maintained intact in all observed photochemical processes, indicating the photochemical stability of this residue under the experimental conditions used and justifying the lack of relevance of the presence in the matrix of several conformers to the observed photochemistry.

After 40 min of irradiation, 48% of the reactant initially present in the matrix had been consumed (see Fig. 10). Considering the relative amounts of the photoproduced species extracted from the experimental spectra (calculated spectra were used as reference data for normalization of the intensities), it was possible to determine the relative efficiencies of the different reaction channels as being b:ca = 8:16:24.

Very interestingly, the observed photochemistry of the matrix-isolated APT is distinct from the preferred photochemical fragmentation in solution, where a different heterocycle, 3,4-dihydro-3-phenyl-pyrimidin-2(1H)-one, is produced as the major photoprodut [20,60]. The lack of formation of phenylpyrimidinone from photolysis of matrix-isolated APT is doubtless related with the matrix environment where the reaction is suppressed. We believe that a strong restriction of conformational mobility in the argon matrix affects not only APT itself, but also its photoproducts. The design of phenylpyrimidinone from APT (after extrusion of N₂) involves an approach between the terminal carbon of the allylic chain and the nitrogen atom N–1, in order to form a new C–N single bond. Such approach is most probably strongly hindered in the rigid matrix. On the other hand, formation of ABZ appears as the main photoreaction channel for APT, in keeping with the results reported by Quast and Nahr [70].

The photochemistry of matrix-isolated 1-phenyl-tetrazoline and APT differ mainly in the secondary fragmentation pathways, essentially because the labile (and much smaller, when compared with the allyl fragment) hydrogen atom in 1-phenyl-tetrazoline confers to the primary photoproducst produced from this compound more flexibility regarding possible subsequent photochemical reactions, in particular under volume-restricted conditions as it is the case of a solid matrix.

2.9. 1-Allyltetrazole (1-ALT) and 2-allyltetrazole (2-ALT)

In 1-ALT and 2-ALT, the orientation of the allyl moiety with regard to the tetrazole ring gives rise to different conformers, whose relative energies stay within 3.5 kJ mol⁻¹ [71]. UV irradiation (λ > 280 nm) of the compounds in argon matrices led to relatively slow consumption of all three conformers of each molecule. Very interestingly, irradiation of both precursors led to the same photo-products, suggesting a common intermediate, 1-allyl-1H-diazirine (Scheme 8).

The main photolysis pathway proceeded through the tetrazole ring cleavage, N₂ elimination and formation of N-allylcarbodiimide as the main product. Two other species, allylcyanamide and allylnitriiline were also detected in the irradiated matrices (Scheme 8).

2.10. Tetrazole coupled with another heterocycle

Heterocycles find wide applications in coordination chemistry as ligands and, among them tetrazoles are known to play an
important role. It has been demonstrated that the heterocycle tetrazole is able to participate in at least nine distinct types of coordination modes with metal ions in the construction of novel metal-organic frameworks [72]. In addition to the relevance of tetrazoles as ligands in catalysis, the coordination ability of the tetrazolyl ligand through four nitrogen electron-donating atoms allows it to serve as a bridging building block in supramolecular assemblies [72]. Especially relevant in this context are bis-tetrazole molecules or conjugates where the tetrazole ring is linked to other heterocycles. In all these systems, a detailed investigation of the structure, including tautomeric and conformational preferences of the molecules, and of their thermal and photochemical stability, is of crucial relevance to define properties and function.

Recently, tetrazole-triazole, tetrazolylpyridines and tetrazole-benzoisothiazole conjugates were studied, with the aim of exploring their potential as multidentate nitrogen ligands.
In all classes tetrazole is connected to another electron-withdrawing heterocycle, directly or through a linker. Some of the molecules prepared were deeply investigated regarding their structure and/or their photochemical stability, as is the case for 5-(1H-tetrazol-1-yl)-1,2,4-triazole, 2-(tetrazol-1-yl)-, 3-(tetrazol-1-yl)- and 2-(tetrazol-5-yl)pyridines and 2-[1-(1H-tetrazol-5-yl)ethyl]-1,2-benzisothiazol-3(2H)-one 1,1-dioxide [27,41,73–76]. The matrix photochemistry of these conjugates, described below, led to the identification and characterization of new molecules: 1H-1,2,4-triazol-5-yl carbodiimide, 1H-1,2,4-triazol-3-yl carbodiimide, pyridin-2-yl carbodiimide, pyridin-3-yl carbodiimide, 1-cyclopenta-2,4-dienylketenimine, 2-[1-(1H-diaziren-3-yl)ethyl]-1,2-benzisothiazol-3(2H)-one 1,1-dioxide, 2-(1,1-dioxide-3-oxo-1,2-benzisothiazol-2(3H)-yl)propanenitrile and 7-thia-8-azabicyclo[4.2.0]octa-1,3,5-triene 7,7-dioxide.

2.10.1. 5-(1H-tetrazol-1-yl)-1,2,4-triazole (T)

In the studied tetrazole-triazole heterocycles are directly connected through a C-N bond (Fig. 11). The 5-(1H-tetrazol-1-yl)-1,2,4-triazole molecule (T) may exist in five tautomeric forms, differing by the position of the H atom in the triazole ring. The tautomers of T will be named here according to the triazole ring atom number where the annular hydrogen atom is attached, from T1 to T5 (Fig. 11). According to calculations (B3LYP/6–311++G(2d,2p)) [41], the lower energy minima correspond to tautomers T1, T2 and T4, where the annular H atom is attached to nitrogen atoms N-1, N-2 and N-4 of the triazole ring. In the global minimum (T1), the annular H-7 atom is attached to the N-1 atom of triazole and this structure is stabilized by a favorable NH···N inter-ring interaction. The next in stability order are two conformers of the T2 tautomer: T2a and T2b (relative energies: 3.6 and 6.9 kJ mol⁻¹, respectively), followed by tautomer T4 (24.6 kJ mol⁻¹). In T4, despite the existence of the same NH···N inter-ring stabilizing interaction as in T1, the relative energy is much higher. This observation was ascribed to the destabilizing effect introduced by two vicinal nitrogen atoms in triazole ring (N-1 and N-2) having the same hybridization. Similar destabilizing effect of such neighborhood was encountered in other molecules [77].

The calculations revealed also the existence of two pairs of conformers of high energy isomers of the compound (T3a, T3b) and (T5a, T5b), in which the annular hydrogen is connected to the C-3 or C-5 atoms, respectively [41].

Bands due to both tautomers T1 and T2 can be identified in the experimental spectrum of a freshly deposited sample. Moreover, trapping T in xenon matrices at 15 K, and subsequent heating of the sample to temperatures to ~30 K (annealing) permitted to induce conformational transformation between conformers T2a and T2b (see Fig. 12), while the population of T1 was not affected by such procedure. This experiment enabled unequivocal spectroscopic characterization of each form to establish the experimental

![Scheme 8](image-url)

**Scheme 8.** Photochemical reactions observed for 1-allyltetrazol (1-ALT) and 2-allyltetrazol (2-ALT), isolated in solid argon, upon irradiation with UV (\(\lambda > 280 \text{ nm}\) light.)

![Fig. 11](image-url)

**Fig. 11.** Tautomers (T1-T5) and conformers (a/b) of tetrazolyl-triazole.
conditions to use during the photochemical studies, where the conformational composition of the molecule was reduced to only two structures (T1 and T2a).

The most spectacular behavior of matrix isolated tetrazole-triazole is its tautomer-selective photochemistry (a similar feature was observed, and discussed above, for 1-(tetrazol-5-yl)ethanol (TE) isolated in solid argon [26]). UV irradiation (λ > 288 nm) of the compound in xenon matrix led to fast consumption of tautomer T1 (ca. 50% in 5 min, almost complete depletion after 30 min), while T2a remained intact. Simultaneously, new bands appeared in the spectrum of the irradiated sample, which must be due to a photochemical product (P1). Upon subsequent irradiation of the matrix with UV-light of shorter wavelengths (λ > 234 nm), the bands due to the T2a tautomer strongly decreased during 25 min of photolysis. At the same time, a set of bands showed up in the spectra, which are due to a second photoproduct (P2).

Fig. 13 shows representative changes in the experimental T/Xe spectra occurring in the process of photolysis with λ > 288 nm filter for T1 and with λ > 234 nm filter for T2a. These changes compared with theoretical simulations showing selective transformations of the T1 and T2a tautomers into the suggested photoproducts, P1 and P2, whose structure is discussed below. Similar broad band UV irradiations (λ > 288 nm and λ > 234 nm) applied to T isolated in argon matrices led to the appearance of sets of bands corresponding to the same photoproducts as observed in xenon matrices.

The main photochemistry pathways resulting from irradiation of the T1 and T2a species in the studied matrices are schematically shown in Scheme 9. The N2 elimination pathway and formation of carbodiimide is the dominating route of the T photolysis. Both T1 and T2a tautomers photolyze according to the same pathway, yielding analogous products differing in the position of the H-atom attached to the triazole ring, 1H-1,2,4-triazol-5-yl carbodiimide (P1) and 1H-1,2,4-triazol-3-yl carbodiimide (P2). The set of bands appearing first in the spectra, at the expense of T1, when lower energy radiation (λ > 288 nm) was applied, fits nicely the calculated spectrum of carbodiimide P1. In turn, the group of bands appearing at the expense of T2, when higher energy radiation (λ > 234 nm) was applied fits very well the carbodiimide P2 spectrum.

According to calculations, the N–N bonds that undergo cleavage in the observed photoreactions are the tetrazole weakest, formally single bonds, longer than 1.360 Å. The formation of the P1 and P2 products proceeds most probably through the 1-(1H-1,2,4-triazol-5-yl)diaziridine and 1-(1H-1,2,4-triazol-3-yl)diaziridine intermediates (Scheme 9). However, these species seem to be rather unstable and were not detected experimentally.

The observed preference for the reaction path leading to the carbodiimide plus N2 is in agreement with the calculated ground-state reaction energies, which are also provided in Scheme 9. It is known that 1,5-disubstituted tetrazoles are useful precursors of carbodiimides (R–N=C=N=R), while 1-substituted tetrazoles give rise to monosubstituted carbodiimides R–N=C=N–H. The latter molecules were found to be stable at low temperatures, but isomerize to cyanamides RNH–CN at ordinary temperatures [78].

2.10.2. 2-(Tetrazol-1-yl)pyridine (Py2T), 3-(tetrazol-1-yl)pyridine (Py3T) and 2-(tetrazol-5-yl)pyridine (PyT)

The title compounds of this subsection are tetrazole derivatives where the tetrazole ring is coupled with the ortho carbon of a
pyridine ring through the N-1 [2-tetrazol-1-yl pyridine (Py2T), 3-tetrazol-1-yl pyridine (Py3T)] or through C-5 atom [2-tetrazol-5-yl pyridine (PyT)].

Py2T and Py3T have one internal rotation axis that gives rise to two different conformational isomers denoted as Py2Ta, Py2Tb and Py3Ta, Py3Tb, respectively [73].

PyT may exist in two tautomeric forms differing in the position of the hydrogen atom in the tetrazole ring. For both PyT tautomers two conformers may exist with different arrangement of the two rings in the molecule, giving altogether four stable forms. All these structures are presented in Fig. 14, where relative energies of the different forms for each compound and their expected gas-phase population at room temperature are also provided. According to the predicted relative energies, in the as deposited argon matrices of the compounds only Py2Ta and PyT1a can be isolated, while in the case of Py3T two conformers could be trapped: Py3Ta and Py3Tb.

Broad-band irradiation of the Py2Ta, Py3Ta/Py3Tb (λ ≤ 280 nm) and PyT1a (λ ≤ 305 nm) species led to cleavage of the tetrazole ring, with the elimination of N2 and the simultaneous formation of pyridin-2-ylcarbodiimide (P1) or pyridin-3-ylcarbodiimide (P2) (Fig. 15). In spite of the different structure of the Py2Ta and PyT1a precursors, the same photoproduct P1 was detected for both species indicating that a carbon-to-nitrogen rearrangement took place in the case of the PyT1a molecule. An additional, unique for the PyT1a precursor, reaction pathway was found consisting

Fig. 14. Py2T, Py3T and PyT isomeric forms. Relative energies (kJ mol⁻¹) and expected population in gas phase at room temperature for the isomers of same compound in parentheses.

Fig. 15. Reactants and final products for the stepwise dissociations on the S₀ surface of PyT1a, Py2Ta and Py3Ta and subsequent P1, P2 or P3 formation. For the detailed mechanisms of these reactions see Ref. [73].

Scheme 9. The main photochemistry pathways resulting from irradiation of the T/Ar and T/Xe matrices. The calculated ground-state reaction energies (ZPE corrected, kJ mol⁻¹) are also shown.
Calculations predicted a total of 6 minima on the ground state potential energy surface of 1-TE-BZT: four minima correspond to the conformers of tautomer 1H and the remaining two to the conformers of tautomer 2H. According to calculations, conformers belonging to the 1H tautomer were found to be the most stable forms. The stabilization of these forms results from the presence of an intramolecular hydrogen bond–like interaction (NH–O=K, where X=S, C) that is absent in both the 2H conformers.

Irradiation of 1-TE-BZT (λ = 275 nm) deposited in a solid argon matrix (only the most stable structure of 1H tautomer was observed in the matrix) induced a prompt decrease of the 1-TE-BZT bands in their IR spectrum with a concomitant observation of new bands corresponding to the photoproduced species. The interpretation of these new bands led to a proposal of different pathways for the photodecomposition of 1-TE-BZT in solid argon Scheme 10 [27], comprising: (a) photolysis of the tetrazole ring with extrusion of N₂ leading to formation of 2-[1-(1H-diaziren-3-yl)ethyl]-1,2-benzothiazol-3(2H)-one 1,1-dioxide; (b) photolysis of the tetrazole ring leading to formation of azide (N₃H) and 2-(1,1-dioxide-3-oxo-1,2-benzothiazol-2(3H)-yl)propanenitrile; (c) photolysis of the saccharyl ring (decarbonylation) and of the tetrazole ring, with formation of azide (N₃H), 7-thia-8-azabicyclo[4.2.0] octa-1,3,5-triene 7,7 dioxide and propene-nitrile.

The relative intensity of bands in the experimental IR spectra of the photolysed matrices indicate that the amount of photoproduces generated in pathway c is higher than that of the photoproducets from pathways a and b. Thus, it appears that the pathway involving photolysis of both the saccharyl and the tetrazolyl rings, is the preferred photodecomposition channel for 1-TE-BZT [27]. Although the photodecomposition of saccharin’s in solution was known [80,81], these results were surprising, since they brought the first observation of photinduced cleavage of the saccharyl core in matrix photochemistry of saccharyl derivatives, leading to decarbonylation. The UV-induced photoisomerization of saccharin in solid argon has been reported very recently, leading to a new compound, isosaccharin [82]. Photolysis of 1-TE-BZT isolated in solid argon led to formation and characterization of three new molecules, specifically: 2-[1-(1H-diaziren-3-yl)ethyl]-1,2-benzothiazol-3(2H)-one 1,1-dioxide, 2-(1,1-dioxide-3-oxo-1,2-benzothiazol-2(3H)-yl)propanenitrile and 7-thia-8-azabicyclo[4.2.0] octa-1,3,5-triene 7,7 dioxide.

Scheme 10. Photochemical reactions observed for 2-[1-(1H-tetrazol-5-yl)ethyl]-1,2-benzothiazol-3(2H)-one 1,1-dioxide isolated in an argon matrix upon irradiation with UV (λ > 275 nm) light.
Table 1
Summary of the primary molecular species formed by photolysis of different matrix-isolated tetrazole derivatives.

<table>
<thead>
<tr>
<th>Tetrazole derivative</th>
<th>Primary photoproduced species</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \text{HN}^-\text{N}^-\text{CH}^-)</td>
<td>( \text{HC}^-\text{N}^-\text{NH} ) nitrilimine, ( \text{H}_2\text{C}^-\text{N}^-\text{N}^- ) diazomethane, ( \text{HN}^-\text{C}^-\text{NH} ) carbodiimide, ( \text{H}_2\text{N}^-\text{C}^-\text{E}^-\text{N} ) cyanamide</td>
</tr>
<tr>
<td>( \text{H}^-\text{N}^-\text{N}^-\text{N}^-\text{H} )</td>
<td>( \text{HO}^-\text{C}^-\text{E}^-\text{N} ) 2-hydroxypropanenitrile</td>
</tr>
<tr>
<td>( \text{R}^-\text{O}^-\text{N}^-\text{N}^- )</td>
<td>( \text{R}^-\text{O}^-\text{C}^-\text{E}^-\text{N} ) alkoxy-cyanate, ( \text{R}^-\text{O}^-\text{C}^-\text{N}^-\text{N}^- ) alkoxy-isocyanate, ( \text{O}^-\text{C}^-\text{N}^-\text{N}^- ) phénylazide</td>
</tr>
<tr>
<td>( \text{H}_2\text{C}^-\text{N}^-\text{N}^-\text{N}^-\text{NH}_2 )</td>
<td>( \text{H}_2\text{N}^-\text{N}^-\text{CH}_3 ) 1-methyl-1( \text{H} )-diazirene-3-amine methylenimine cyanamide</td>
</tr>
<tr>
<td>( \text{N}^-\text{N}^-\text{N}^-\text{N}^-\text{H} )</td>
<td>( \text{H}_2\text{N}^-\text{N}^-\text{CH}_3 ) 1-methyl-1( \text{H} )-diazirene-3-amine methylenimine cyanamide</td>
</tr>
<tr>
<td>( \text{N}^-\text{N}^-\text{N}^-\text{N}^-\text{H} )</td>
<td>( \text{H}_2\text{C}^-\text{C}^-\text{N}^-\text{N}^- ) 1-phenyl-diaziridine-3-thiol</td>
</tr>
<tr>
<td>( \text{N}^-\text{N}^-\text{N}^-\text{N}^-\text{N}^-\text{O} )</td>
<td>( \text{HN}^-\text{N}^-\text{N}^-\text{N}^-\text{O} ) 3-phenyl-2,3-dihydotetrazete phenylidiazene</td>
</tr>
<tr>
<td>( \text{N}^-\text{N}^-\text{N}^-\text{N}^-\text{N}^-\text{O} )</td>
<td>( \text{HN}^-\text{N}^-\text{N}^-\text{N}^-\text{O} ) 3-phenyl-2,3-dihydotetrazete phenylidiazene</td>
</tr>
<tr>
<td>( \text{N}^-\text{N}^-\text{N}^-\text{N}^-\text{O} )</td>
<td>( \text{HN}^-\text{N}^-\text{N}^-\text{N}^-\text{O} ) 3-phenyl-2,3-dihydotetrazete phenylidiazene</td>
</tr>
<tr>
<td></td>
<td>( \text{HN}^-\text{C}^-\text{O} ) 1-aza-1,2,4,6-cycloheptatetraene isocyanate</td>
</tr>
</tbody>
</table>

\( \text{N}^-\text{N}^-\text{N}^-\text{N}^-\text{O} \) phenylazide
Table 1 (continued).

<table>
<thead>
<tr>
<th>Chemical Structure</th>
<th>Name</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1" alt="Chemical Structure" /></td>
<td>1-allyl-1H-benzoimidazol-2(3H)-one</td>
</tr>
<tr>
<td><img src="image2" alt="Chemical Structure" /></td>
<td>1-allyl-2-phenylazidin-3-one</td>
</tr>
<tr>
<td><img src="image3" alt="Chemical Structure" /></td>
<td>phenylisocyanate</td>
</tr>
<tr>
<td><img src="image4" alt="Chemical Structure" /></td>
<td>1-aza-1,2,4,6-cycloheptatetraene</td>
</tr>
<tr>
<td><img src="image5" alt="Chemical Structure" /></td>
<td>phenylazide</td>
</tr>
<tr>
<td><img src="image6" alt="Chemical Structure" /></td>
<td>allylazide</td>
</tr>
<tr>
<td><img src="image7" alt="Chemical Structure" /></td>
<td>allylisocyanate</td>
</tr>
<tr>
<td><img src="image8" alt="Chemical Structure" /></td>
<td>allylcarbodiimide</td>
</tr>
<tr>
<td><img src="image9" alt="Chemical Structure" /></td>
<td>allylcyanamide</td>
</tr>
<tr>
<td><img src="image10" alt="Chemical Structure" /></td>
<td>allylnitrilimine</td>
</tr>
<tr>
<td><img src="image11" alt="Chemical Structure" /></td>
<td>1H-1,2,4-triazol-5-yl carbodiimide</td>
</tr>
<tr>
<td><img src="image12" alt="Chemical Structure" /></td>
<td>1H-1,2,4-triazol-3-yl carbodiimide</td>
</tr>
<tr>
<td><img src="image13" alt="Chemical Structure" /></td>
<td>pyridin-2-yl carbodiimide</td>
</tr>
<tr>
<td><img src="image14" alt="Chemical Structure" /></td>
<td>pyridin-3-yl carbodiimide</td>
</tr>
<tr>
<td><img src="image15" alt="Chemical Structure" /></td>
<td>1-cyclopenta-2,4-dienylketenimine</td>
</tr>
<tr>
<td><img src="image16" alt="Chemical Structure" /></td>
<td>2-(1,1-dioxide-3-oxo-1,2-benzisothiazol-2(3H)-yl)propanenitrile</td>
</tr>
<tr>
<td><img src="image17" alt="Chemical Structure" /></td>
<td>2-[1-(1H-diaziren-3-yl)ethyl]-1,2-benzisothiazol-3(2H)-one 1,1-dioxide</td>
</tr>
<tr>
<td><img src="image18" alt="Chemical Structure" /></td>
<td>azide</td>
</tr>
<tr>
<td><img src="image19" alt="Chemical Structure" /></td>
<td>7-thia-8-azabicyclo[4.2.0] octa-1,3,5-triene 7,7-dioxide</td>
</tr>
<tr>
<td><img src="image20" alt="Chemical Structure" /></td>
<td>propene-nitrile</td>
</tr>
</tbody>
</table>
3. Conclusions

The use of matrix isolation technique coupled to a suitable probing method, such as FTIR spectroscopy, represents an accurate strategy to understand the mechanisms involved in photochemical reactions, its main advantages being the simplification of the photochemical processes due to cage confinement of the reactions and the possibility to achieve a high spectroscopic resolution, increasing the probability to detect chemical species produced in low amounts during photolysis or those with intrinsically low intensity IR absorptions. Then, matrix isolation represents then a powerful tool to investigate the photochemistry of tetrazole derivatives.

According to our results, the fundamental photochemistry of matrix-isolated tetrazoles involves fragmentation of the tetrazole ring. The specific substituents present in the ring determine in large amount the preferences for the different available primary photochemical reaction channels and strongly determine secondary processes in which the initial photoproducts participate. As a general rule, the tetrazole ring can undergo photolytic cleavage in three different ways: (a) through the (N-1)–(N-2) and (N-3)–(N-4) bonds, releasing molecular nitrogen and forming a diazirine derivative; (b) through the (N-1)–(C-5) and (N-3)–(N-4) bonds and (c) through (N-1)–(N-2) and (N-4)–(C-5) bonds. In the two latter cases, the precise nature of the photoproducts varies depending on the substituents present in the tetrazole ring, but one of the products is always an azide, which then can undergo subsequent reactions, most of times eliminating N₂ to form the nitrile that then can further react to form the final product (e.g., ACHT, produced by ring expansion of phenyl nitrile).

The number of available reaction channels correlates with the number of formally single bonds in the tetrazole ring. When four single bonds are present (like in tetrazolones or tetrazole-thiones), the 3 photochemical fundamental types of reactions can take place, a fourth reaction path being sometimes also activated, corresponding to cleavage through the (N-1)–(C-5) and (N-4)–(C-5) bonds. For all molecules we investigated exhibiting only three formally single bonds in the tetrazole ring, only two reaction channels were found to be active, with that corresponding to direct N₂ elimination always playing the most important role.

The presence in the ring or in the substituents of labile hydrogen atoms always increases the complexity of the photochemistry, mainly due to the occurrence of different tautomerisms, whereas the conformational flexibility of the substituent may have effects difficult to predict a priori. These are strongly determined by the number and relative energies of the possible conformers and conformational interconversion barriers.

The presence of a phenyl substituent at N-1 (or N-4) in alkylxoy tetrazoles results in strong activation of the channel leading to production of phenylazide and the corresponding alkyl-cyanate (that undergoes major isomerization to the isocyanate). In tetrazolones and tetrazole-thiones, a phenyl or alkyl substituent at N-1 (or N-4) favors the pathway leading to direct production of the corresponding isocyanate or thionocyanate, which is in general inhibited in the alkylxoy and alkyloxy tetrazoles.

The mechanism for direct elimination of molecular nitrogen from the tetrazole ring was not yet fully explained, but it seems that it occurs mainly through the biradical intermediate [20,21] that subsequently undergoes cyclization and forms diazirine. The biradical has been recently observed in an investigation carried out in our laboratory on substituted tetrazoles in solution, by laser flash-photolysis [21]. The mechanisms for the remaining two prototype primary ring-cleavage photochemical reactions of the tetrazole ring are still to be investigated.

It is fortunate that most of the prevalent photoproducts of the photochemistry of tetrazole derivatives can be reliably identified by IR spectroscopy. In fact, three groups of bands, occurring in usually clean spectral regions allow easy identification of the main products resulting from the three fundamental paths in tetrazoles' photochemistry: diazirines and diaziridinones give rise to characteristic bands in the 1800–1900 cm⁻¹ spectral region, azides have their most intense band around 2100 cm⁻¹ (νN=N-N antisymmetric stretching) and isocyanates strongly absorb in the 2290–2300 cm⁻¹ range (νN≡C=O antisymmetric stretching).

A final note shall be made regarding the possibility of using the in situ photolysis of matrix-isolated tetrazoles to produce novel molecular species (see structures in Table 1), like for example intermolecular diazirines, diaziridines, carbodiimides, nitriles, reactive isocyanates, azides and tetrozates (e.g., 3-methoxy-1-phenyl-1H-diazirine, 3-ethoxy-1-phenyl-1H-diazirine, 3-allyloxy-1-phenyl-1H-diazirine, 1-phenyl-diaziridin-3-one, 1-allyl-2-phenyl-diaziridin-3-one, 1H-1,2,4-triazol-5-yl carbodiimide, 1H-1,2,4-triazol-3-yl carbodiimide, 1-methyl-1,2-dihydrotetrazete, 3-phenyl-2,3-dihydrotetrazete, allylisocyanate, allylazide).

Acknowledgements

The authors are grateful to Fundação para a Ciência e Tecnologia (FCT, Portugal), FEDER and COMPETE-QUER-EU [Projects PEst-C/MAR/LA0015/2011, PTDC/QUI-QUI/111879/2009; PTDC/QUI-QUI/118078/2010, FCOMP-01-0124-FEDER-021082, and Grant SRH/BPD/43853/2008 (L.M.T. F.)]. A.G.Z. [member of the research career from the Argentinean National Research Council (CONICET)] acknowledges support from the Argentinae Agency for the Scientific and Technical Promotion [(ANPCyT) Project PICT(2011)/0226].

References
