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Synthesis, Spectroscopic and Thermal Characterization of Azido-1,2,4-triazoles: A Class of Heteroarenes with a High Nitrogen Content

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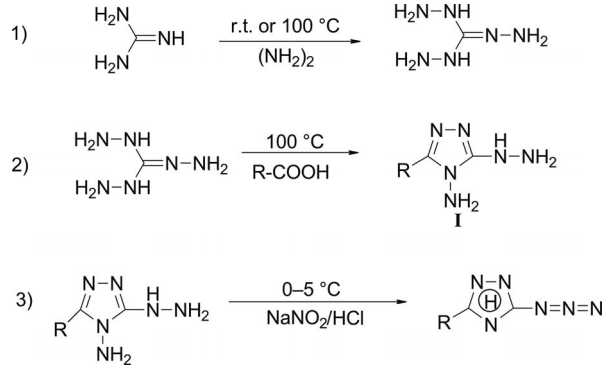
The syntheses of azido-1,2,4-triazoles **1**–**5** were carried out from triaminoguanidine hydrochloride and a carboxylic acid (formic, acetic, 2,2,2-trifluoroacetic, 2-benzylacetic, monochloroacetic acid) by a three-step synthetic route and were analyzed by accelerating rate calorimetry (ARC). The thermal decomposition of **1**–**5** was studied theoretically by using CHETAH and T1 software, and experimentally by using DSC to obtain kinetic data. Numerical modelling and mass spectrometry were also performed to estimate the nature of the intrinsic molecular reactivity of **1**–**5** and the possible early stages of a self-heating process. Complete optimization by using HF, B3LYP and MP2(full) methods at the 6-31G* level were performed on significant tautomeric forms of the azido-triazoles to confirm the electronic structures that were obtained by EI-MS.

Introduction

Azides derived from five-membered heteroarenes play an increasing role in chemistry,[1] and their synthesis has stimulated overwhelming interest.[2] To date, the great majority of heteroaryl azides have been obtained by the aromatic nucleophilic displacement of various nucleofuge groups with an azido ion, by diazotization of heteroarylamines followed by the addition of sodium azide or the conversion of hydrazines to azides by diazotization.[3] A number of five-membered azido heteroarenes with one or two heteroatoms have been successfully produced in our laboratory by the azido transfer reaction with regioselectively lithiated heteroaryls and tosyl azide.[4]

Our long-term interest in the field of the heteroaryl azides prompted us to study an extension to azido-1,2,4-triazoles, some of which are virtually unknown. This study was carried out in view of the chemical, thermal, theoretical and biological importance of the 1,2,4-triazole system, which has been shown to be a tunable aryl/alkyl ionic liquid.[5] The 1,2,4-triazole substructure has been incorporated into a wide variety of therapeutically important agents, which mainly display antimicrobial[6] and anti-inflammatory activities.[7] Normally, 1,2,4-triazoles with non-equivalent 3- and 5-substituents crystallize as tautomers that bear substituents with more pronounced electron-donor properties at the 5-position.[8] Additional impetus was given to this work by the fact that, to the best of our knowledge, only two azido-triazoles (1,2,4-triazolyl azide **1** and methyl-1,2,4-triazolyl azide **2**, Scheme 1) have been prepared to date, but their isomeric structures have not been ascertained.[9]



Scheme 1. Three-step synthesis of **1**–**5**; R = H, CH_3, CF_3, CH_2Ph, CH_2Cl.

The synthetic route to azido-1,2,4-triazoles **1**–**5** described here is a combination of two reactions: a cyclocondensation by heating triaminoguanidine hydrochloride (TAG·HCl) with an excess of the appropriate carboxylic acid (Scheme 1, Step 2) followed by diazotization of the (aminotriazolyl)-hydrazine intermediate **I** with 2 equiv. of sodium nitrite (Step 3). TAG·HCl was prepared from guanidine hydrochloride and 3 equiv. of hydrazine hydrate at room temperature in water (Step 1).

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We were also interested in the conversion of the previously reported routes to 1,2,4-triazoles for **1** and **2** into a three-step "green" route. Green chemistry and chemical safety are linked concepts that should be applied when potentially hazardous compounds are involved.[10]

The thermochemical properties of nitrogen-rich covalent azides and their potential use as high-energy-density materials are under continuous investigation.[11] Attention has been recently paid to the energetic content of compounds as triazolium-based ionic salts,[12] which contribute to high heats of formation and high energetic densities, but no thermal behaviour has been reported on this class of neutral species. The only exception is a study on the gas-phase flash-pyrolysis of 3-azido-1,2,4-triazole, which results in the elimination of nitrogen and formation of *N*-cyanomethanimine (CH_2=N–CN) presumably via a nitrene intermediate.[13] Compounds **1**–**5** were selected as significant examples of a series of nitrogen-rich covalent azides whose dangerous threshold values, given by the molecular composition ratio (C + O + S)/N, are ≤ 3, and to shed light on the role of both the substituent and the azido group on thermal decomposition (TD) phenomena. The hazardous properties of this class of oxygen-free compounds are attributed to the easy polarization of the $–N_3$ π-bond, which facilitates N_2 extrusion.[14] Many organic compounds that contain one (or more) azido group(s) are thermally (or mechanical shock) sensitive.[15]

Interest in these potentially explosive molecules has grown as researchers have overcome their awe of the hazard posed by handling azides.[16] In spite of the fact that organic azides are generally stable towards common oxidants and acidic aqueous solutions, azides with large positive heats of formation (Δ_fH) are inherently unstable. The underlying reasons for the reactivity or lack of stability of a molecule can be elucidated by examining its thermodynamic parameters and by scrutinizing its (a) kinetic variables,[11b,11c] (b) critical temperatures,[17] (c) numerical protocols based on its symmetry and geometry, (d) spatial distributions and energies of a few dominant orbitals and (e) electric polarizabilities and hyperpolarizabilities.

Results and Discussion

According to the synthetic route described above (Scheme 1), TAG·HCl was prepared from guanidine hydrochloride (1 equiv.) and hydrazine hydrate (3 equiv.) in boiling water or at room temperature (Step 1).[18] 1*H*-1,2,4-Triazol-5-yl azide (**1**), 3-methyl-1*H*-1,2,4-triazol-5-yl azide (**2**), 5-(trifluoromethyl)-1*H*-1,2,4-triazol-3-yl azide (**3**), 5-benzyl-1*H*-1,2,4-triazol-3-yl azide (**4**) and 3-(chloromethyl)-1*H*-1,2,4-triazol-3-yl azide (**5**) were prepared from an excess of the corresponding carboxylic acid (formic, acetic, 2,2,2-trifluoroacetic, 2-phenylacetic and monochloroacetic acid, respectively) and TAG·HCl by cyclocondensation to hydrazinyl-1,2,4-triazolylamino intermediates (**I**, Step 2) and converted into the corresponding target azido-1,2,4-triazoles by the diazotization of the amino and hydrazino groups on **I** (Step 3). The risk of Steps 1 and 3 was analyzed by accelerating rate calorimetry (ARC, see Exp. Sect.).[19]

Differential scanning calorimetry (DSC)[20] of TAG·HCl in static nitrogen (Φ = 5 °C min^{-1}) showed less dangerous exothermic decomposition at T_p = 225 °C (Δ_dH = 1166 $J\,g^{-1}$) compared to other TAG salts.[21] To maintain a parallel between the experimental results and electronic-structure calculations, various isomeric structures of TAG have been reported by using ab initio molecular orbital (MO) and density functional methods.[22]

Theory

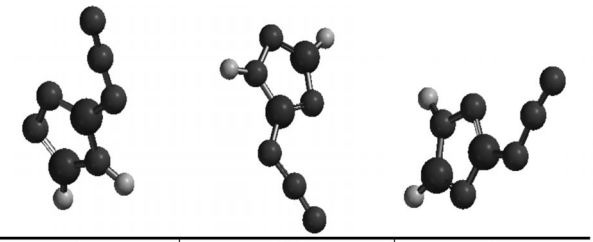
Structural characterization of **1**–**5** was made by IR and ^1H and ^{13}C NMR spectroscopy and MS in combination with electronic methods. Complete optimization was performed on various isomers of each triazole to determine the energy and geometrical parameters by using HF, B3LYP[23] and MP2(Full)[24] methods at the 6-31G* level of calculations (Table 1).

Table 1. Calculated absolute energies [a.u., zero-point energy (ZPE) corrected values], density [ρ, g/mL] and heat of formation [Δ_fH, $kJ\,mol^{-1}$] (T1) for the favoured isomeric structures of **1**–**5**.

	B3LYP/6-31+G*	MP2(FC)/6-31G*	ρ	Δ_fH
1a	–405.760266	–404.654038	0.7464	566.67
1b	**–405.772144**	**–404.664637**	–	537.17
1c	–405.770004	–404.662583	–	537.40
2a	–445.053855	–443.800346	–	523.71
2b	**–445.065423**	**–443.810762**	0.9290	495.03
2c	–445.057823	–443.803633	–	505.48
3a	–742.794577	–740.223598	–	–92.09
3b	–742.794832	–740.227316	–	–110.30
3c	**–742.799141**	**–740.232491**	0.8850	–117.12
4a	–676.030034	–673.521779	–	621.88
4b	–676.028236	–673.519257	–	609.51
4c	**–676.040001**	**–673.532333**	0.6290	592.70
5a	–904.656129	–902.830695	–	475.74
5b	–904.658682	–902.831700	–	488.39
5c	**–904.664538**	**–902.840035**	0.7861	503.73

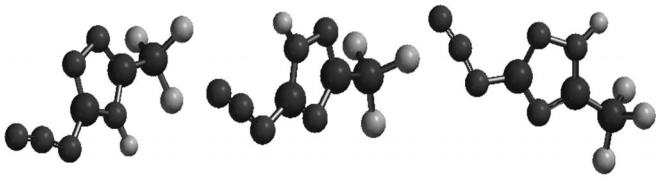
The azido group is involved in π-electron interaction with the 1,2,4-triazole nucleus, which is dependent on the nature of the substituent. As an example, Figures 1 and 2 depict the prototropic electronic structures (**1a**, **1b**, **1c** and **3a**, **3b**, **3c**, respectively) and their significant geometric parameters (the absolute energies of the more stable prototropic isomers are in bold in Table 1). In all cases, the azido group is oriented in the same plane as the heteroaryl triazole ring, similar to 3,6-diazido-1,2,4,5-tetrazine,[11d] triazidotrinitrobenzene and azidothymidine.[25]

Most work on simple 2-azido-azole molecules (thiazole and imidazole) has focussed on azido–tetrazole isomerism, which has been extensively studied experimentally[26] and theoretically.[27] Figure 3 depicts the triazolo–tetrazoles **Tet-1**–**5** hypothesized at the MP2(FC)/6-31G* level, and Table 2 reports the energetic values of the most stable isomer (T1) for each substituent calculated by ab initio MO and density functional methods.



Parameters	1a	1b	1c
∠N-C-N_1-N_2	0.0	0.0	0.0
∠Het-N_1-N_2N_3	114.5	114.3	115.5
∠ HetN_1-N_2-N_3	171.8	172.1	171.5
Å	1.397	1.397	1.402
Å	1.253	1.251	1.249
Å	1.159	1.159	1.162

Figure 1. Molecular modelled tautomeric structures (**a**, **b**, **c**) and some geometric parameters [° and Å] for **1** calculated at the MP2(FC)/6-31G* level.



Parameters	3a	3b	3c
∠N-C-N_1-N_2	0.0	0.0	0.0
∠Het-N_1-N_2N_3	115.3	116.9	115.5
∠ HetN_1-N_2-N_3	171.4	171.7	171.5
Å	1.398	1.396	1.398
Å	1.251	1.249	1.251
Å	1.161	1.163	1.161

Figure 2. Molecular modelled tautomeric structures (**a**, **b**, **c**) and some geometric parameters [° and Å] for **3** calculated at the MP2(FC)/6-31G* level.

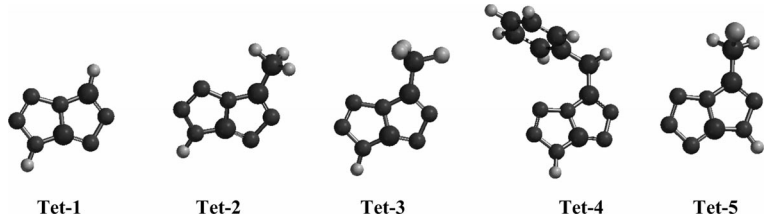


Figure 3. The most stable tautomeric structures for **Tet-1**–**5** calculated at the MP2(FC)/6-31G* level.

Table 2. Calculated absolute energies [a.u., ZPE-corrected values], ρ [g/mL] and $\Delta_f H$ [kJ mol^{-1}] (T1) for the most stable isomers of **Tet-1**–**5**.

	B3LYP/6-31+G*	MP2(FC)/6-31G*	ρ	$\Delta_f H$
Tet-1	–405.737313	–404.631496	0.7706	701.69
Tet-2	–445.033189	–443.768791	0.7162	590.04
Tet-3	–742.765759	–740.866486	0.9067	–18.03
Tet-4	–676.001630	–676.031632	0.6391	701.50
Tet-5	–904.641010	–902.833857	0.8071	628.38

By comparison, calculations for the possible isomers **Tet-1**–**5** are summarized in Table 2, which confirm the linear azido preference shown by azido–diazoles.[2a,4a]

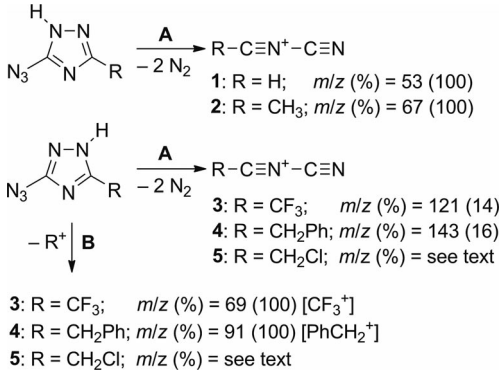
In order to predict and detect the early-stage processes involved in the TD of **1**–**5**, theoretical calculations by using CHETAH (chemical thermodynamic and hazard evaluation)[28] and T1[29] software packages and EI-MS (70 eV) were performed. The data calculated with CHETAH for the azido–triazoles are listed in Table 3.

$\Delta_d H$ values for **1**–**4** were predicted to be over the threshold of –2930 J g^{-1}, above which compounds are considered dangerous, whereas that of **5** was undetermined due to the absence of a Benson group.[30] Moreover, comparison of the CHETAH-predicted heats of formation ($\Delta_f H$) with those obtained by using the computationally less intensive thermochemical recipe T1, revealed that the values obtained by using the two approaches are comparable (cf. Tables 1 and 3).

Table 3. Calculated (CHETAH) heats of combustion [$\Delta_c H$, J g^{-1}], decomposition ($\Delta_d H$, J g^{-1}), formation ($\Delta_f H$, kJ mol^{-1}) and N–N_2 bond energies (B3LYP/6-31G*) [kJ mol^{-1}] of **1**–**5**.

	$\Delta_c H$	$\Delta_d H$	$\Delta_f H$	E_{N-N2}
1	–1569.6	–5250.9	540.57	111.0
2	–2172,0	–5365.9	507.64	104.0
3	–1310.6	–3345.2	–141.37	118.8
4	–5123.9	–3815.8	614.71	135.5
5	–	–	–	209.2

The calculated absolute energies (Table 1) of **1**–**5** indicate that the nature of the substituent on the triazole ring substantially affects the prototropy of these compounds, where **1b** and **2b** of the type 3-R-5-azido-1*H*-1,2,4-triazole (R = H, CH_3) are favoured with respect to **3c**, **4c** and **5c** of the type 3-azido-5-R-1*H*-1,2,4-triazole (R = CF_3, CH_2Ph and CH_2Cl). Accordingly, the nature of R affects the EI mass spectra, which show different fundamental fragmentation by the pathways **A** and **B** (Scheme 2). Unexpectedly, attempts to record the EI mass spectra of **5** under the same conditions failed.



Scheme 2. Structural dependence of the main EI mass spectra fragmentation of **1**–**5**.

The calculated prototropic forms (Table 1, **a**–**c**) show an energy gap of 10–40 kJ mol^{-1}, which might be too low to markedly affect the thermal behaviour of structures that have a heat of formation tenfold larger.

DSC enabled us to characterize the thermal stability of **1**–**5**. The experimental heats of decomposition obtained by DSC and the related initial exothermal onset temperature (T_{EOT}) are shown in Table 4.

Table 4. DSC-determined heat of decomposition [J g^{-1}], temperature [°C] and kinetic parameter [E_a, kJ mol^{-1}] for the TD of **1**–**5** under various conditions.[a]

Compd.	$\Delta_d H$[b]	$\Delta_d H$[c]	T_{EOT}[d]	T_p[e]	T_{EET}[f]	E_a[g]	ln A°[h]
1	2245	2270	160	186	209	126.18	27.97
2	2025	1725	160	186	215	123.99	27.34
3	1355	1190	160	193	213	129.39	28.30
4	790	790	155	187	206	126.07	27.26
5	1675	1681	130	179	197	122.79	27.59

[a] TD data refer to a scan rate (Φ) of 5 °C min^{-1}. [b] In static air. [c] Under nitrogen. [d] Exothermic onset temperature. [e] Peak decomposition temperature. [f] Exothermic endset temperature. [g] From thermoanalytical data obtained by using the ASTM E698 method. [h] Frequency factor [min^{-1}].

The DSC profiles, the example of **2** is shown in Figure 4, measured at different heating rates from 90 to 200 °C, were analyzed by using the ASTM E698 method. From a plot of log$b$ (b = heating rate in °C min^{-1}) against 1/T (T = peak temperature in °C), the activation energies (E_a), the preexponential factor (A^0) and the kinetic constant (k) for each

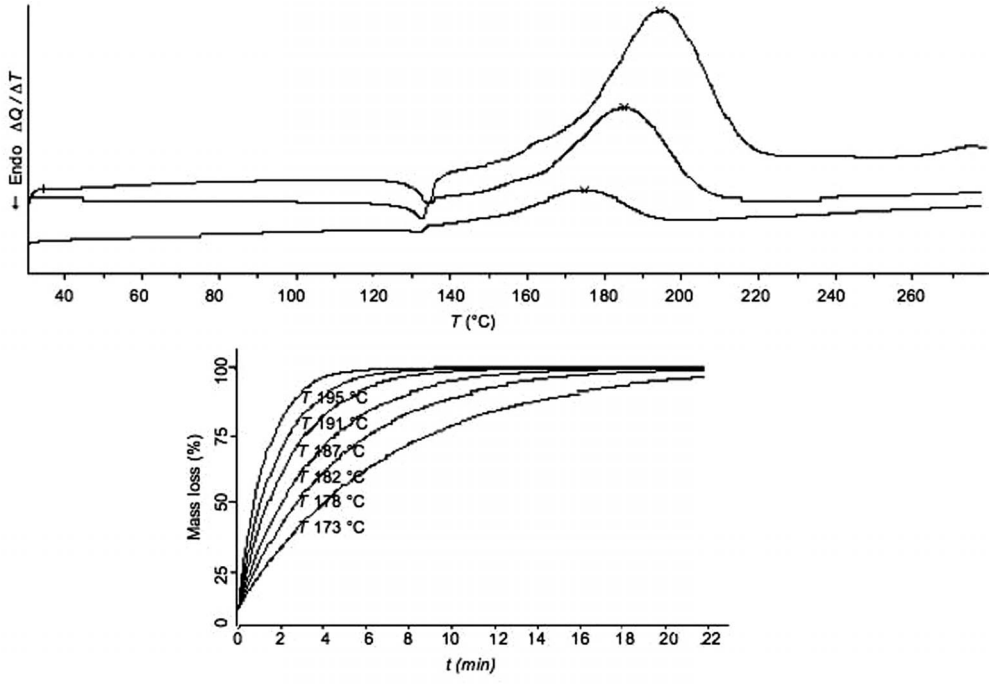


Figure 4. DSC experiments performed under nitrogen at scanning rates (Φ) of 2, 5 and 10 °C min^{-1} of **2** (top) and DSC kinetic evaluation results of **2**, conversion [%] vs. time [t, min] at various temperatures (bottom).

Table 5. Kinetic parameters and activation energies for the TD of **1**–**5** calculated from thermoanalytical data obtained by using the ASTM E698 method.[a]

	1	**2**	**3**	**4**	**5**
k / min^{-1}	1.403×10^{12}	7.475×10^{11}	1.952×10^{12}	1.389×10^{12}	9.598×10^{11}
E_a / $kJ\,mol^{-1}$	126.8	124.0	129.4	126.1	122.8
$\Delta_r H$ / $kJ\,mol^{-1}$	123.7	121.5	126.9	123.6	120.3
S_a[b] / $K^{-1}\,mol^{-1}$	–0.17	–0.18	–0.19	–0.19	–0.18

[a] DSC data refer to four runs at heating rates of 2, 5, 10 and 15 °C min^{-1} in static nitrogen. [b] Calculated at 298 K.

absolute temperature can be calculated. The data obtained for **1**–**5** are reported in Table 4.

The TD reactions of **1**–**5** were treated as having first-order kinetics as plots of $\ln k$ vs. T show a linear trend with correlation coefficients R = 0.999. The E_a values of **1**–**5** were calculated with corresponding $\ln A^0$ values. Assuming a unimolecular processes, we calculated the activation enthalpies ($\Delta H^{\ddagger}$) and entropies (ΔS_a) from the data (Table 5).

The ASTM-calculated half-lives and the corresponding E_a values for the TD of **1**–**5** at 25 °C were comparable. This implies substantially comparable thermal behaviour, which can be ascribed to the extrusion of nitrogen and formation of a nitrene without the assistance of the R substituents. This was also confirmed by the slightly negative S_a values.

Conclusions

The three-step synthetic route to asymmetric azido-1,2,4-triazoles **1**–**5** appears to be applicable to different low-melting aliphatic acids in a closed procedure. The chemical efficiency at low temperature for Steps 1 and 3, the low cost of reagents, the generally high product yields and the use of water as the medium make this process ecofriendly. The risk of Steps 1 and 3 (Scheme 1) at room temperature was ascertained by ARC. An ARC test on Step 2 was unsuccessful.

The potentially hazardous properties and thermochemical behaviour of **1**–**5** were investigated by DSC, NMR and FTIR spectroscopy and EI-MS. The TD of **2**–**3** and **5** display medium to high exothermicity, higher for **1** and lower for less nitrogen-containing **4**. TD generally occurs without the assistance of oxygen, and both the ring and the azido group fragmentation result in the loss of 2 equiv. of nitrogen and cyanogen.

On the whole, the molecular modelling performances agree with the respective tautomeric structures observed by EI-MS and support their thermal properties, which show relatively more energetic decomposition for azido–triazoles that contain no substituent or the methyl-releasing group (**1** and **2**, respectively).

Experimental Section

Physical Measurements and Calculations: The initial thermochemical data were calculated by the ASTM program for chemical thermodynamic and energy release evaluation (CHETAH, ver. 8.0, 2005).[28] The heats of formation obtained by this method were compared with those calculated by using a recently released Spartan 06 code, T1.[29] Thermal performances were measured relative to a reference sample with DSC 820 and DSC 823 Mettler Toledo instruments with the following accuracy standards: (i) 5 °C min^{-1} for the evaluation of decomposition enthalpy under both oxidative and closed steel vessel nonoxidative conditions from 30 to 280 °C, (ii) 2, 5 and 10 °C min^{-1} for the evaluation of kinetic data from dynamic heating under nitrogen in a closed steel vessel from 30 to 280 °C, unless otherwise stated.[31] Thermogravimetric analysis, which measured weight loss under both oxidative and nonoxidative heating conditions in an open vessel, allowed the IR and mass spectra of the released gases to be recorded (TGA-DSC 1LF/164 from Mettler Toledo, Nexus FTIR from Thermo Fischer Scientific, Pfeiffer Vacuum Thermostar MS spectrometer). The melting points of **1**, **2**, **4** and **5**, were 120.3, 132.5, 143.2 and 69.3 °C, respectively, obtained from DSC and were in agreement with previously measured values.

Materials: The synthetic route, which was slightly modified with respect to those previously described, is a "green" processes. The basic reaction steps that allow the access to **1**–**5**, the formation of TAG·HCl and the nitrosation of the hydrazinyl-1,2,4-triazolylamino intermediates, were studied by ARC in a process hazard assessment. Guanidine hydrochloride, hydrazine hydrate, sodium nitrite and the carboxylic acids (formic, acetic, 2,2,2-trifluoroacetic, 2-benzylacetic, monochloroacetic acid) were purchased at high purity from Aldrich Chemical Italy.

ARC Tests: The ARC (TIAX) tests were carried out according to ASTM specifications (E1981-98 Standard Guide for Assessing the Thermal Stability of Materials by Methods of Accelerating Rate Calorimetry).

Step 1. Triaminoguanidine Synthesis: Total sample amount: 2.96 g. Test cell type: Hastelloy C. Test cell weight: 13.95 g. Test cell volume: 8 ml. Φ factor: 1.61. A mixture of guanidine hydrochloride (0.4 g), hydrazine hydrate (0.6 g) and water (2.0 g) was loaded in the sample holder at room temperature. A standard Heat Wait Search (HWS) test was set up in the 30–300 °C range with magnetic stirring (50 rpm). Initial decomposition temperature, T_o = 170 °C. Initial pressure (at T_o) = 14.7 bar. Maximum self-heating rate (SHR, Φ-corrected) = 0.2 °C min^{-1}. Temperature at maximum SHR, T_{max} = 188 °C. pressure at T_{end} = 40.6 bar. Φ-corrected adiabatic temperature rise = 46 °C. Φ-corrected final temperature = 216 °C. Decomposition enthalpy = –193 $kJ\,kg^{-1}$. At the end of the test at room temperature, a residual pressure of 14.5 bar and a sample weight loss of 33.4% were observed, which means that the sample generated noncondensable decomposition products.

Step 2. Nitrosation of the Hydrazinyl-1,2,4-triazolamine: Total sample amount: 4.78 g. Test cell type: Hastelloy C. Test cell weight: 14.12 g. Test cell volume: 8 mL. Φ factor: 1.55. Hydrazinyl-1,2,4-triazolamine solution (2.85 g) was loaded in the sample holder at room temperature. A standard HWS test was set up in the 30–300 °C range and with magnetic stirring (50 rpm). During the search period at 30 °C, $NaNO_2$ (0.7 g) in water (1.23 g) was added through a syringe. The instrument detected an exothermic effect as soon as the $NaNO_2$ solution was added, which resulted in a large

amount of gas. Some of the gas was vented during the addition through the open charge tube of the instrument. After the first exothermic effect, other two exothermic consecutive effects were detected and monitored in adiabatic mode by the instrument. The main results of the first exothermic effect are: starting temperature, T_o = 30 °C. Initial pressure at T_o = 1.2 bar. Maximum SHR (Φ-corrected) = 136 °C min^{-1}. temperature at maximum SHR, T_{max} = 36 °C. Pressure at T_{end} = 1.5 bar. Observed adiabatic temperature rise = 34 °C. Φ-corrected temperature rise = 52 °C. Φ-corrected final temperature = 82 °C. Reaction enthalpy = –152 kJ kg^{-1}. The main results of the second exothermic effect are: T_o = 64 °C. Initial pressure at T_o = 1.5 bar. Maximum SHR (Φ-corrected) = 1 °C min^{-1}. Temperature at maximum SHR, T_{max} = 101 °C. Pressure at T_{end} = 16.0 bar. Φ-corrected adiabatic temperature rise = 110 °C. Φ-corrected final temperature = 174 °C. Decomposition enthalpy = –322 kJ kg^{-1}. At the end of the test at room temperature, a residual pressure of 21 bar was observed, which means that the sample generated noncondensable decomposition products.

Caution: Organic azides are potentially explosive! This category of compounds has been subjected to risk evaluation.[15,16] Explosions may occur in the preparation and handling of organic azides, although we experienced no problems in handling our aryl or heteroaryl organic azides, which can be stored indefinitely at low temperature (4 °C).

Instrumentation: Melting points were determined with a Kofler hot-stage apparatus. IR spectra were measured from films with a Perkin–Elmer Spectrum 2000 FTIR spectrometer. ^{1}H and ^{13}C NMR spectra were recorded with a Varian Gemini 300 (300 and 75.4 MHz, respectively) from solutions in $(CD_3)_2CO$ or $CDCl_3$. Mass spectra were recorded with VG7070E instruments by using an electron impact ionization method (70 eV) at the same pressure (10^{-7} atm) and temperature (27 °C). Calculations were performed by using the program Spartan 06 (Windows), DFT and MP2 methods at B3LYP/6-31G* and MP2/6-31G* levels, running on an AMD K7 processor at 1333 MHz by which optimized structures and energetics of the N–N_2 bond dissociation were obtained.

Synthesis 1–5. General Procedure: A suspension of TAG·HCl (2.1 g, 0.015 mol) in liquid carboxylic acid (35 mL; formic acid: b.p. 100.8 °C; acetic acid: b.p. 118–119 °C; 2,2,2-trifluoroacetic acid: b.p. 72.4 °C) was heated at 70–100 °C for 4–16 h. The resulting mixture that contained the hydrazinyl-1,2,4-triazolamine intermediate **I** (approximate yield: ca. 90–95%) was combined with concentrated HCl (25 mL), and the resulting solution heated. In the instance of solid carboxylic acids (2-phenylacetic acid: m.p. 76–77 °C; monochloroacetic acid: m.p. 63 °C), TAG·HCl was added to the melted acid and the route carried out as described. The excess volatile carboxylic acid was removed under partial vacuum and recovered. With 2-phenylacetic and monochloroacetic acids, a few extractions with diethyl ether were required. The residual acidic solution was combined with water (25 mL) and added dropwise at 0–5 °C to a saturated aqueous solution of $NaNO_2$ (0.033 mol, 2.3 g) over 30 min until gas evolution ceased. The solution was warmed to room temperature and stirred for 30 min, neutralized (pH = 6.5) with solid $NaHCO_3$ and extracted with diethyl ether (3 × 20 mL). Upon concentration of the ethereal solution under vacuum, the resulting solid residues (oily in the case of **3**) were stored overnight in a refrigerator and characterized by IR and ^{1}H and ^{13}C NMR spectroscopy, elemental analysis and MS.

1*H*-1,2,4-Triazol-5-yl Azide (1): Yield: 87%. M.p. 121–23 °C. $C_2H_2N_6$ (110.08): calcd. C 21.82, H 1.83, N 76.35; found C 21.78, H 1.82, N 76.30. IR: $\tilde{\nu}_{max}$ = 2148 (N_3) cm^{-1}. ^{1}H NMR (300 MHz, [D_6]acetone): δ = 12.75 (N–H), 8.55 (C–H) ppm. ^{13}C NMR (75 MHz, [D_6]acetone): δ = 144.2, 140.8 ppm. MS: *m*/*z* (%) = 110 (32.8) [M^+], 82 (7.9) [$M–N_2]^+$, 53 (100) [M – 57]$^+$.

3-Methyl-1*H*-1,2,4-triazol-5-yl Azide (2): Yield: 88%. M.p. 128–30 °C. $C_3H_4N_6$ (124.10): calcd. C 29.03, H 3.25, N 67.72; found C 28.92, H 3.23, N 67.67. IR: $\tilde{\nu}_{max}$ = 2147 (N_3) cm^{-1}. ^{1}H NMR (300 MHz, $CDCl_3$): δ = 10.5 (N–H), 2.52 (3 H, Me) ppm. ^{13}C NMR (75 MHz, $CDCl_3$): δ = 157.4, 155.3, 12.2 (t) ppm. MS: *m*/*z* (%) = 124 (3.8) [M^+], 67 (100) [M – 57]$^+$.

5-Trifluoromethyl-1*H*-1,2,4-triazol-3-yl Azide (3): Yield: 67%, oil. $C_3HF_3N_6$ (178.07): calcd. C 20.23, H 0.57, N 47.19; found C 20.18, H 0.57, N 47.18. IR: $\tilde{\nu}_{max}$ = 2156 (N_3), 1187 (CF_3) cm^{-1}. ^{13}C NMR (75 MHz, $CDCl_3$): δ = 153.5, 152.5 (q, *J* = 0.8 Hz), 118.8 (q, *J* = 5.4 Hz) ppm. MS: *m*/*z* (%) = 178 (8.1) [M^+], 159 (3.0) [M – F]$^+$, 137 (7.1), 121 (13.4) [M – 57]$^+$, 69 (100).

5-Benzyl-1*H*-1,2,4-triazol-3-yl Azide (4): Yield: 77%. M.p. 146–48 °C. $C_9H_8N_6$ (200.20): calcd. C 53.99, H 4.03, N 41.96; found C 53.95, H 4.02, N 41.88. IR: $\tilde{\nu}_{max}$ = 2140 (N_3) cm^{-1}. ^{1}H NMR (300 MHz, $CDCl_3$): δ = 10.5 (N–H), 7.28 (br. m, 5 H, Ph), 4.07 (2 H, CH_2) ppm. ^{13}C NMR (75 MHz, $CDCl_3$): δ = 158.5, 157.7, 135.2, 129.5, 129.3, 128.0, 33.7 ppm. MS: *m*/*z* (%) = 200 (3.8) [M^+], 143 (16.4) [M – 57]$^+$, 121 (16.0), 92 (100).

3-(Chloromethyl)-1*H*-1,2,4-triazol-3-yl Azide (5): Yield: 76%. M.p. 69–73 °C. $C_3H_3ClN_6$ (158.59): calcd. C 22.73, H 1.91, N 53.01; found C 22.68, H 1.90, N 52.98. IR: $\tilde{\nu}_{max}$ = 2143 (N_3), 728 (Cl) cm^{-1}. ESI: *m*/*z* = 159 [M + 1]$^+$, 181 [M + 23]$^+$. ^{1}H NMR (300 MHz, $CDCl_3$): δ = 8.80 (N–H), 4.67 (2 H, CH_2) ppm. ^{13}C NMR (75 MHz, $CDCl_3$): δ = 156.7, 155.6, 35.9 ppm.

Supporting Information (see footnote on the first page of this article): ARC tests main results for steps 1 and 2, including figures showing the heat rate and pressure rate plots vs. test cell temperature under adiabatic conditions related to the exothermic effect. Temperature and pressure plots vs. time and pressure plot vs. temperature related to the whole test. Heat rate and pressure rate plots vs. test cell temperature under adiabatic conditions for the three exothermic effects. Temperature and pressure plots vs. time related to the exothermic effect and pressure plot vs. temperature related to the whole experiment. DSC profiles of the TD and plot of the kinetic evaluation for azides **1**–**5**.

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