

Cite this: *RSC Adv.*, 2017, 7, 38951

Oxidative addition/cycloaddition of arenesulfonamides and triflamide to *N*-allyltriflamide and *N,N*-diallyltriflamide†

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N-Allyltriflamide adds triflamide in the oxidative system (*t*-BuOCl + NaI) to give *N,N',N''*-propane-1,2,3-triyltris(triflamide), while under the same conditions arenesulfonamides as well as trifluoroacetamide diastereoselectively give the product of chlorination/dimerization, (2*R*,5*S*)-2,5-bis(chloromethyl)-1,4-bis[(trifluoromethyl)sulfonyl]piperazine. *N,N*-Diallyltriflamide reacted with triflamide affords the products of iodotriflamidation of one or two C=C bonds, and the product of intramolecular iodotriflamidation, 3,7-diiodo-1,5-bis[(trifluoromethyl)sulfonyl]-1,5-diazocane, and 3,7,9-tris[(trifluoromethyl)sulfonyl]-3,7,9-triazabicyclo[3.3.1]nonane. In contrast, with arenesulfonamides and trifluoroacetamide, *N,N*-diallyltriflamide gives the products of iodoamidation or/and iodochlorination at only one double bond.

Received 25th May 2017
Accepted 3rd August 2017

DOI: 10.1039/c7ra05831d

rsc.li/rsc-advances

Introduction

The chemistry of triflamide (CF₃SO₂NH₂ or TfNH₂) and its derivatives has attracted the attention of chemists due to its high acidity, catalytic activity¹ and specific chemical properties which are different from those of other sulfonamides, as was clearly demonstrated in our review.² Of special interest are unsaturated derivatives of triflamide, because the presence of a multiple bond affected by a very strong electron-acceptor triflyl group increases the synthetic potential of these compounds. Until recently, very scarce information was available not only on unsaturated triflamide compounds but also for other sulfonamides as well. The first representative of *N*-alkenyltriflamides was synthesized by us in 2012.³ Since then, numerous unsaturated triflamide compounds having one or two double or/and triple bonds have been synthesized and investigated in different reactions.⁴

Another fascinating field of the triflamide chemistry is the reactions of oxidative triflamidation of alkenes and dienes, leading in many cases to the products different from those obtained with arenesulfonamides.⁵ A similar specific reactivity was observed in the reactions of oxidative trifluoroacetamidation in comparison with the reactions of non-fluorinated amides.⁶ However, depending on the substrate and the oxidant, triflamide may show the same pattern of

reactivity as arenesulfonamides, like it was demonstrated very recently on the example of chloroamidation of a large series of indoles with triflamides and arenesulfonamides with NaClO as an oxidant.⁷ In all cases, the products of substitution (*via* addition–elimination), 3-chloro-2-amidoindoles, were obtained in moderate to excellent yields.

It was reasonable to assume that the study of the reactions combining these two types of transformations, that is, the reactions of oxidative triflamidation of unsaturated triflamide derivatives, would lead to new unusual structures and specific patterns of reactivity. With this in mind, in the present study we have studied the reactions of *N*-allyltriflamide TfNHCH₂CH=CH₂ **1** with triflamide **2** and, for comparison, with arenesulfonamides 4-RC₆H₄SO₂NH₂ (R = Me, H, Cl, NO₂) **3a–d** and trifluoroacetamide **4** under oxidative conditions in the system (*t*-BuOCl + NaI). The reaction of *N,N*-diallyltriflamide TfN(CH₂-CH=CH₂)₂ **5** with triflamide has also been studied to investigate the effect of the substrate on the course of the reaction.

The reaction of *N*-allyltriflamide with triflamide at –30 °C proceeds in quantitative yield and affords a single product identified as *N,N',N''*-propane-1,2,3-triyltris(triflamide) **6** (Fig. 1). The structure of product **6** was proved by ¹H, ¹³C, ¹⁹F NMR and IR spectroscopy and elemental analysis (Scheme 1).

For comparison, we performed under the same conditions the reaction of *N*-allyltriflamide **1** with arenesulfonamides **3a–d** (R = Me, H, Cl, NO₂) and with trifluoroacetamide CF₃CONH₂ **4**. To our surprise, for the reaction both with **3** and with **4** the only product isolated in good yield was piperazine **7**. That means, that both arenesulfonamides and trifluoroacetamide act only as chlorine carriers, irrespective of their NH-acidity, which is much lower than that of triflamide (p*K*_a vary from 11.70 for **3a** to 9.48 for **3d** and are equal to and 6.39 for TfNH₂ and >14 for **4**).

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† Electronic supplementary information (ESI) available: Detailed synthetic procedures, IR and NMR spectra of all new products, and X-ray structural analysis data. CCDC 1545539, 1520697 and 1520698. For ESI and crystallographic data in CIF or other electronic format see DOI: 10.1039/c7ra05831d

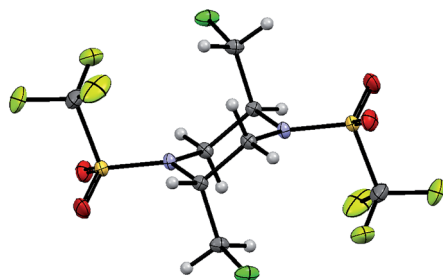
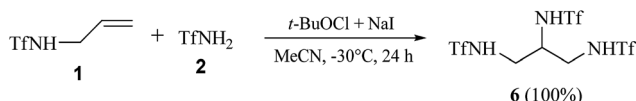


Fig. 1 ORTEP diagram of (2*R*,5*S*)-2,5-bis(chloromethyl)-1,4-bis[(trifluoromethyl)sulfonyl]piperazine **7**.⁹



Scheme 1 Oxidative addition of triflamide **2** to *N*-allyltriflamide **1**.

However, the yield tends to increase with the decrease of pK_a of the amide (Table 1).

The structure of product **7** was deduced from its IR, mass, ^1H and ^{13}C NMR spectra, in particular, from the absence of NH signals in ^1H NMR as well as ν_{NH} band in IR spectrum, the presence of two pairs of diastereotopic methylene protons in the range 3.6–4.1 ppm, with respect to one unresolved multiplet of methine proton at 4.25 ppm, and the corresponding ^{13}C signals at 40, 42 and 55 ppm as well as one CF_3 quartet at 120 ppm. The mass spectrum showed a low-intense peak of molecular ion with m/z 446 and most intense ions with m/z 397 [$\text{M} - \text{CH}_2\text{Cl}$] and 263 [$\text{M} - \text{CF}_3\text{SO}_2 - \text{HCl}$], all with proper isotope distribution. Finally, the molecular structure was determined by single crystal X-ray analysis as (2*R*,5*S*)-2,5-bis(chloromethyl)-1,4-bis[(trifluoromethyl)sulfonyl]piperazine **7** (Fig. 1).⁸ Molecule **7** has S_2 mirror-rotation axis (or inversion centre C_i) passing through the center of the ring and parallel to the S– CF_3 and C– CH_2Cl bonds.

It is worth noting that *N*-allylamides with other electron-withdrawing groups like Ts, PhCO or PhCS, show essentially different behaviour: in the same oxidative system they undergo intramolecular cyclization with the formation of 2-iodomethyl-*N*-tosylaziridine, 5-iodomethyl-2-phenylisoxazole or -thiazole, respectively.¹⁰ This means that, as in many other cases, unsaturated triflamide **1** exhibit specific reactivity which is distinct from that of other sulfonamides in similar reactions. The reasons for that were outlined by us earlier.²

Under the same conditions, *N,N*-diallyltriflamide **5** gives a whole bunch of linear and cyclic products in a moderate total yield and in comparable amounts depending on the reaction conditions (Scheme 3). With equimolar ratio of the reagents at -10°C , the reaction mixture contains monoadduct **8**, 3,7-diiodo-1,5-bis(trifluoromethylsulfonyl)-1,5-diazocane **10** and 3,7,9-tris(trifluoromethylsulfonyl)-3,7,9-triazabicyclo[3.3.1]nonane **11**, along with a small amount of unreacted substrate **5**. Increasing the ratio of **5** to **2** to 1 : 2 and carrying out the reaction at -30°C results in full conversion of the reagents and

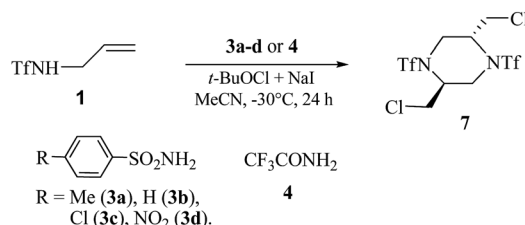
Table 1 Chlorination–dimerization of *N*-allyltriflamide **1** with different amides in the system (*t*-BuOCl + NaI)^a

Entry	X	Conversion	Yield ^b (%)
1	$\text{MeC}_6\text{H}_4\text{SO}_2$	70	50
2	$\text{C}_6\text{H}_5\text{SO}_2$	51	76
3	$\text{ClC}_6\text{H}_4\text{SO}_2$	43	53
4	$\text{NO}_2\text{C}_6\text{H}_4\text{SO}_2$	69	86
5	CF_3CO	64	46

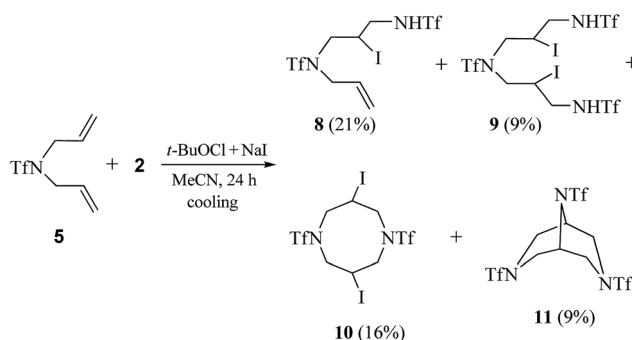
^a Reaction conditions: 8 mmol of **1**, 8 mmol of **3a–d** or **4**, 24 mmol of NaI, 24 mmol of *t*-BuOCl in 80 ml of CH_3CN was stirred for 24 h at -30°C in argon atmosphere in the dark. ^b Isolated yields.

formation of diadduct **9**, apart from products **8**, **10**, **11**. All reaction products were isolated as individual compounds by column chromatography and their structure was determined by ^1H , ^{13}C , ^{19}F NMR spectroscopy and, for compounds **10** and **11**, also by single crystal X-ray analysis, Fig. 2 and 3, respectively. Molecule **10** has C_2 symmetry axis, and molecule **11** has the plane of symmetry passing through the sulfur and nitrogen atoms.

As with *N*-allyltriflamide **1**, we performed the reaction of *N,N*-diallyltriflamide **5** with arenesulfonamides **3a–d** and with trifluoroacetamide CF_3CONH_2 **4**. The reaction occurred only at



Scheme 2 Oxidative cyclodimerization of *N*-allyltriflamide **1** in the presence of NsNH_2 .



Scheme 3 Oxidative addition/cycloaddition of triflamide **2** to *N,N*-diallyltriflamide **5**.



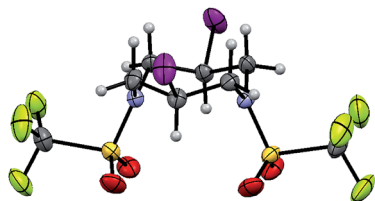


Fig. 2 ORTEP diagram of 3,7-diiodo-1,5-bis(trifluoromethylsulfonyl)-1,5-diazocane **10**.¹¹

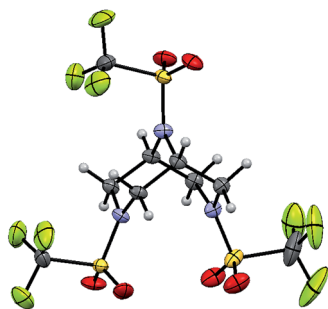


Fig. 3 ORTEP diagram of 3,7,9-tris(trifluoromethylsulfonyl)-3,7,9-triazabicyclo[3.3.1]nonane **11**.¹²

one double bond leading to the products of iodoamidation **12** similar to **8**, and their isoelectronic analogue **13** (Table 2). No addition to the second C=C bond takes place even with double excess of sulfonamide (on the example of $\text{NO}_2\text{C}_6\text{H}_4\text{SO}_2\text{NH}_2$). The reasons for such inertness of the second double bond in **5** with respect to addition of sulfonamides are not clear; the only assumption is that the oxidative addition to one double bond decreases the reactivity with respect to further reaction with electrophiles, which may require harsher conditions, in which the reaction mixture undergoes resinification.

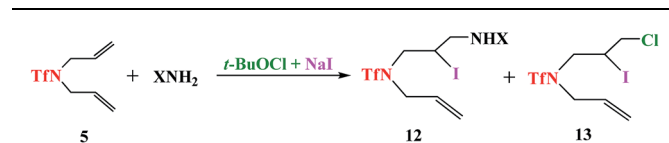
One-pot assembling of 1,5-diazocane and 3,7,9-triazabicyclo[3.3.1]nonane scaffolds shown in Scheme 3 is of interest because it was shown that the presence of the 1,5-diazocane motif in oxidative polyamine metabolites is critical for inhibiting activity and suppressing cytotoxicity.¹³ The known methods of synthesis of 1,5-diazacyclooctanes suffer from costly reagents¹⁴ or long-term processes (up to nine days).¹⁵ The present work provides the first one-pot synthesis of 3,7-diiodo-1,5-bis[(trifluoromethyl)sulfonyl]-1,5-diazocane capable of further functionalization at positions 3 and 7.

As to 3,7,9-triazabicyclo[3.3.1]nonane derivatives, their synthesis is based on the cyclization of compounds having the 2,4-bis(chloromethyl)piperidine moiety under the action of amines.¹⁶

The mechanism of oxidative triflamidation of compound **1** is similar to that proposed earlier and includes, as the key intermediate reagent, *N*-iodotriflamide **14**,^{5d} which adds to the double bond of substrate **1** affording intermediate adduct **15**. The latter reacts with the next molecule of **14** with elimination of molecular iodine and formation of the final product **6** (Scheme 4).

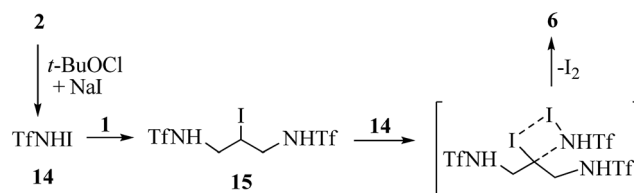
Unexpected formation of substituted piperazine **7** in the reaction in Scheme 2 could be indicative of the reaction

Table 2 Iodoamidation/iodochlorination of *N,N*-diallyltriflamide **5** with different amides in the system (*t*-BuOCl + NaI)^a



Entry	X	Conversion	Yield ^b (%)	
			12	13
1	$\text{MeC}_6\text{H}_4\text{SO}_2$	25	42	—
2	$\text{C}_6\text{H}_5\text{SO}_2$	41	29	41
3	$\text{ClC}_6\text{H}_4\text{SO}_2$	45	—	43
4	$\text{NO}_2\text{C}_6\text{H}_4\text{SO}_2$	44	—	42
5	CF_3CO	67	31	—

^a Reaction conditions: 7 mmol of **5**, 7 mmol of **3a–d** or **4**, 20 mmol of NaI, 20 mmol of *t*-BuOCl in 50 ml of CH_3CN was stirred for 24 h at -30°C in argon atmosphere in the dark. ^b Isolated yields taking into account the conversion.



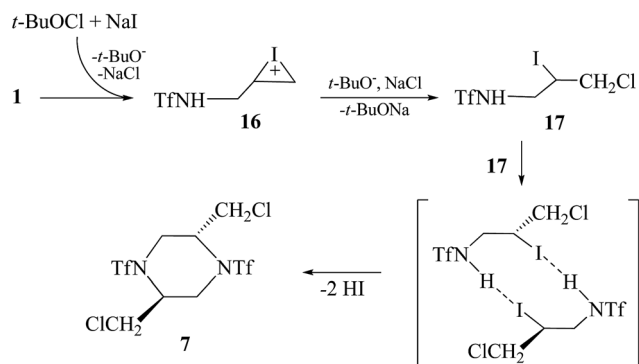
Scheme 4 A tentative mechanism of oxidative triflamidation of *N*-allyltriflamide **1**.

proceeding without sodium iodide being involved. However, a special experiment showed that the formation of **7** does not occur in the absence of NaI. This allowed us to suggest the following tentative mechanism, shown in Scheme 5 and including the intermediate iodonium cation **16**, its opening with the formation of adduct **17**, and subsequent cyclo-dimerization to the final product **7**.

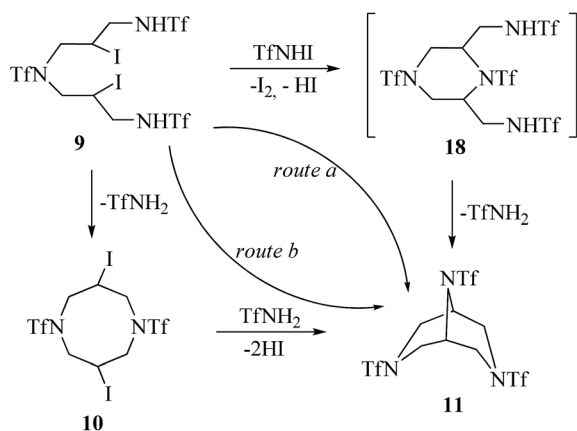
Consideration of the structure of cation **17** allows to explain the X-ray structure with two axial CH_2Cl substituents in the ring. Since the bond configuration around the triflamide nitrogens is planar, the adjacent chloromethyl groups adopt axial positions in the pre-formed six-membered ring after elimination of HI in order to minimize repulsions between the triflyl and chloromethyl substituents leading to the experimentally determined structure (Fig. 1).

The mechanism of formation of the bicyclic product **11** depends on the fate of diadduct **9** (Scheme 6). Route a suggests its cyclization to the intermediate *N,N'*-[1,4-bis(trifluoromethylsulfonyl)piperazine-2,6-diyl]dimethanediyl bis(triflamide) **18**, which finally gives bicycle **11** by elimination of the triflamide molecule. An alternative route b is hardly possible since the two iodine atoms in the 8-membered cycle **10** are too far from each other being in the equatorial positions of the *chair,chair*-conformation of the 3,7-diiodo-1,5-bis[(trifluoromethyl)sulfonyl]-1,5-diazocane **10** molecule. Indeed,





Scheme 5 A tentative mechanism for the formation of (2R,5S)-2,5-bis(chloromethyl)-1,4-bis[(trifluoromethyl)sulfonyl]piperazine 7.



Scheme 6 Possible routes to 3,7,9-tris[(trifluoromethyl)sulfonyl]-3,7,9-triazabicyclo[3.3.1]nonane 11.

special experiment showed that compound 10 taken separately was not converted to bicycle 11 under the reaction conditions, *via* route b.

Conclusions

In summary, we have shown that unsaturated derivatives of triflamide, being involved as substrates in oxidative reactions with triflamide and arenesulfonamides in the system (*t*-BuOCl + NaI), give a series of new linear, cyclic and bicyclic products, whose structure depends on the reaction conditions and the nature of the reagents. With *N*-allyltriflamide, triflamide and arenesulfonamides show quite different reactivity patterns: bis-triflamidation in the former case and chlorination–dimerization in the latter. The reasons why triflamide enters the reactions of oxidative addition whereas arenesulfonamides and trifluoroacetamide act only as positive chlorine carriers are to be examined separately.

Acknowledgements

All spectroscopic and X-ray measurements were performed on the equipment of the Baikal Center of Collective Use of Siberian Branch of the Russian Academy of Sciences.

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- 8 Crystallographic data were collected on a Bruker D8 Venture, μ (Mo K α) = 0.7107 mm⁻¹ at *T* = 100 K. All structures were solved and refined on *F* by using the SHELXS-2013 program. Crystal data for 7: C₈H₁₀Cl₂F₆N₂O₄S₂, monoclinic, space group *P*2₁/*c* (no. 14), *Z* = 4, *a* = 8.8090(4) Å, *b* = 12.7998(6) Å, *c* = 7.2200(3) Å, β = 91.795(2)°, *V* = 813.68(6) Å³, *D*_c = 1.825 g cm⁻³; 2 θ _{max} = 60.1°; 21 282 reflections and 2381 with *I* > 2 σ (*I*); 109 parameters (C, O, N, S, F, I, Cl anisotrope, H isotrope); maximum residual electron density 0.43 e Å⁻³; *R*₁ = 0.026, *wR*₂ = 0.064. Crystal data for 10: C₈H₁₀F₆I₂N₂O₄S₂, monoclinic, space group *P*2₁/*c*



- (no. 14), $Z = 8$, $a = 11.305(2) \text{ \AA}$, $b = 17.982(3) \text{ \AA}$, $c = 18.058(3) \text{ \AA}$, $\beta = 100.15(1)^\circ$, $V = 3613.5(9) \text{ \AA}^3$, $D_c = 2.316 \text{ g cm}^{-3}$; $2\theta_{\max} = 60.3^\circ$; 147 899 reflections and 10 609 with $I > 2\sigma(I)$; 434 parameters (C, O, N, S, F, I anisotrope, H isotrope); maximum residual electron density 2.09 e \AA^{-3} ; $R_1 = 0.043$, $wR_2 = 0.089$. Crystal data for **11**: $\text{C}_9\text{H}_{10}\text{F}_9\text{N}_3\text{O}_6\text{S}_3$, triclinic, space group $P\bar{1}$ (no. 2), $Z = 4$, $a = 11.214(4) \text{ \AA}$, $b = 11.857(5) \text{ \AA}$, $c = 14.834(7) \text{ \AA}$, $\alpha = 73.27(1)^\circ$, $\beta = 78.95(1)^\circ$, $\gamma = 80.98(1)^\circ$, $V = 1848.0(1) \text{ \AA}^3$, $D_c = 1.883 \text{ g cm}^{-3}$; $2\theta_{\max} = 60.2^\circ$; 40 457 reflections and 9983 with $I > 2\sigma(I)$; 541 parameters (C, O, N, S, F anisotrope, H isotrope); maximum residual electron density 1.48 e \AA^{-3} ; $R_1 = 0.079$, $wR_2 = 0.22$.
- 9 Selected bond distances (\AA) for **7**: C(2)–C(3) 1.527(2), C(3)–C(4) 1.528(2), C(2)–N(1) 1.480(1), C(3)–N(1) 1.482(1), C(4)–Cl(1) 1.785(1), C(1)–S(1) 1.8362(14), S(1)–O(1) 1.423(1), S(1)–N(1) 1.606(1), C(1)–F(1) 1.325(2).
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 - 11 Selected bond distances (\AA) for **10**: C(3)–C(4) 1.520(6), C(2)–C(4) 1.513(5), C(2)–N(2) 1.483(2), C(3)–N(1) 1.490(2), C(6)–C(7) 1.519(4), C(7)–C(8) 1.515(5), C(6)–N(1) 1.482(3), C(8)–N(2) 1.490(3), C(4)–I(1) 2.159(3), C(7)–I(2) 2.165(3). The I...I interatomic distance is 7.7 \AA .
 - 12 Selected bond distances (\AA) for **11**: C(2)–C(3) 1.533(5), C(3)–C(4) 1.535(3), C(2)–N(1) 1.476(2), C(3)–N(3) 1.479(2), C(7)–C(8) 1.522(4), C(7)–C(9) 1.533(6), C(9)–N(1) 1.467(2), C(8)–N(2) 1.465(3), C(4)–N(2) 1.480(3), C(7)–N(3) 1.485(3).
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