



Communication

Mechanistic study of the addition reaction of TeCl_4 to alkynes: Participation of TeCl_3 centered-radicalArtur F. Keppler^a, Fernanda M. Prado^a, Giselle Cerchiaro^b, Paolo Di Mascio^a, João V. Comasseto^{a,*}^a Instituto de Química, Universidade de São Paulo, Av. Prof. Lineu Prestes, 748, 05508-900 São Paulo, SP, Brazil^b Centro de Ciências Naturais e Humanas, Universidade Federal do ABC, Santo André, SP, Brazil

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ABSTRACT

The mechanism of the addition reaction of TeCl_4 to alkynes was indirectly established by the detection of TeCl_3 centered radicals using EPR spin trapping, ESI-MS and ESI-MS/MS characterization.

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Tellurium chemistry offers alternative routes for a number of classical organometallic processes [1]. The unique stereochemical control associated with various Te-promoted transformations, taken together with the high Te–Li exchange rate [1,2], represent specific advantages associated with the application of organo-Te compounds in synthetic processes [3–7]. Thus, additions of Te(IV) halides to alkynes have been employed in the preparation of bioactive Te-containing compounds, some of which are effective inhibitors of human chatepsine B [8] or exhibit potent antioxidant properties [9]. These reactions are highly stereospecific and occur exclusively via *syn* or *anti* addition, depending on the alkyne employed (Scheme 1) [10]. Whereas proposals of an ionic mechanism for the addition of Te(IV) halides to unsaturated compounds date back to the early days of Te chemistry [10–12], no mechanistic studies of such reactions involving Te(IV) species have been reported.

We have recently reported the characterization of organic Te(II)-centered radicals by EPR spin trapping and by ESI-MS and ESI-MS/MS [13]. In the present study, we explore the possibility of a radical mechanism for the addition of TeCl_4 to alkynes using a similar analytical approach together with EPR isotopic labeling studies. We also report the generation of aryl radicals promoted by the reaction of a TeCl_3 centered-radical with the nitroso spin trap DBNBS [14].

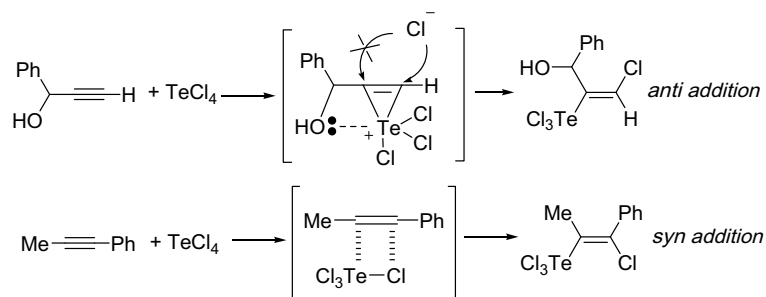
The addition reactions of TeCl_4 to alkynes were performed in benzene. Samples were extracted from the reaction mixtures and examined by EPR in the absence and in the presence of the spin traps DBNBS, DMPO, MNP and PBN [14]. Intense EPR spectra were generated by the samples only in the presence of DBNBS (Fig. 1). All of the reactions studied produced similar EPR spectra, irrespective of the alkyne involved (Table 1, runs 1–5), and displayed a triplet of doublets ($a_N = 12.7$ G, $a_H = 5.65$ G, line width = 2.5 G, $g = 2.0085$) that could be attributed to hyperfine interaction of an unpaired electron spin with the nuclear spin of one nitrogen and one hydrogen atom. The recorded a_N hyperfine splitting constant is characteristic of carbon-centered radicals linked to the nitroso group of the DBNBS spin trap [15].

Samples of reaction mixtures collected at different times during the progress of the addition of TeCl_4 to an alkyne (0–3 h) and incubated with DBNBS, presented similar EPR signal intensities indicating that the DBNBS radical adduct maintained the same instantaneous concentration throughout the course of the reaction. The DBNBS radical adducts so-formed were stable for 2 h after which time they decayed slowly to non-radical species, probably by radical reduction as inferred by ESI-MS analysis.

In an attempt to substantiate the hypothetical attack of a TeCl_3 centered-radical on the nitroso group of the DBNBS spin trap, we synthesized $^{125}\text{TeCl}_4$ containing EPR-active Te. The spectra obtained in experiments employing labeled and non-labeled Te halides were similar (Table 1, cf. runs 2 and 6), from which it may be concluded that the Te atom is not in the neighborhood of the unpaired electron. Since sigma-radicals are known to add to benzene

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Scheme 1. Proposed mechanism for the addition reaction of TeCl_4 to alkynes.

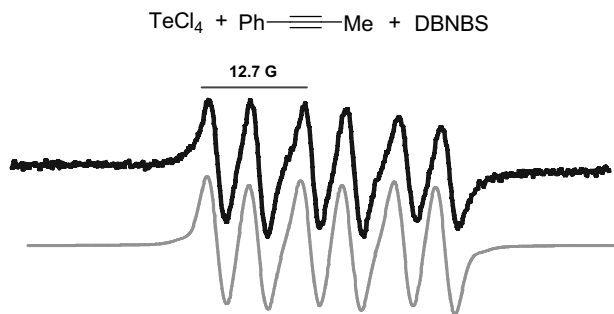


Fig. 1. Representative EPR spectrum obtained following incubation of a sample of a reaction mixture in benzene with methanolic DBNBS for 60 min. The gray line represents a computer simulation of the spectrum (generated using Bruker Symphonia software).

to give cyclohexadienyl radicals [16], the reaction between 1-phenyl propyne and TeCl_4 was performed with benzene- d_6 as solvent in order to examine the potential formation of a DBNBS-cyclohexadienyl radical adduct. This possibility could be excluded, however, since the EPR spectra obtained from experiments involving labeled and non-labeled benzene were similar (Table 1, cf. runs 2 and 7). Having excluded two possible pathways to the formation of the DBNBS radical adduct, it is proposed that a TeCl_3 centered-radical **1** could promote Br-atom abstraction from the DBNBS spin trap **2** generating an aromatic carbon-centered radical **3** in a process similar to that reported for Sn(IV)-centered radicals [17–19]. The radical **3** would then attack the nitroso group of an intact DBNBS

Table 1

Experimental EPR data of the reactions and control experiments performed

Runs	Spectra recorded in benzene/methanol (~1:1 v/v) ^a	EPR hyperfines of DBNBS radical adducts	
		a_N (G)	a_H (G)
1 ^b	$\text{TeCl}_4 + \text{PhC}\equiv\text{CPh} + \text{DBNBS}$	12.7	5.65
2	$\text{TeCl}_4 + \text{MeC}\equiv\text{CPh} + \text{DBNBS}$	12.7	5.65
3	$\text{TeCl}_4 + \text{HC}\equiv\text{CPh} + \text{DBNBS}$	12.7	5.65
4	$\text{TeCl}_4 + \text{HC}\equiv\text{C}(\text{CH}_2)_3\text{CH}_3 + \text{DBNBS}$	12.7	5.65
5	$\text{TeCl}_4 + \text{HC}\equiv\text{CCH}_2\text{OH} + \text{DBNBS}$	12.7	5.65
6 ^c	$^{125}\text{TeCl}_4 + \text{MeC}\equiv\text{CPh} + \text{DBNBS}$	12.7	5.65
7 ^c	$\text{TeCl}_4 + \text{MeC}\equiv\text{CPh}/\text{C}_6\text{D}_6 + \text{DBNBS}$	12.7	5.65
8 ^c	$\text{TeCl}_4 + \text{MeC}\equiv\text{CPh} + \text{DBNBS}/\text{MeOD-}d_4$	12.7	5.65
9 ^c	$\text{TeCl}_4 + \text{DBNBS}$	No signal	
10 ^c	$\text{MeC}\equiv\text{CPh} + \text{DBNBS}$	No signal	
11 ^c	$\text{Me}(\text{Cl})=\text{C}(\text{Ph})\text{TeCl}_3 + \text{DBNBS}$	No signal	

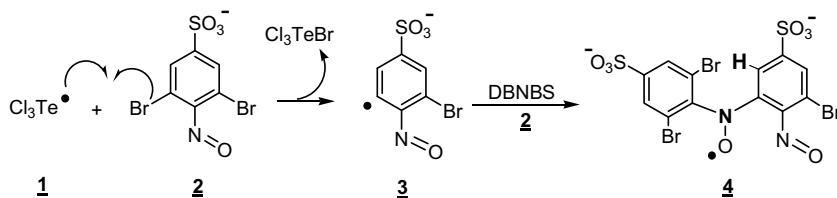
^a All spectra were measured after reaction mixtures had been incubated with a methanolic solution of DBNBS for 60 min. Analyzed samples comprised benzene/methanol solutions with final concentrations equivalent to 2.2 mM alkyne, 2.0 mM TeCl_4 and 6.0 mM DBNBS.

^b Incubation time was 10 min.

^c Control experiments.

molecule (Scheme 2) producing the DBNBS radical adduct **4**, the proposed structure of which is in agreement with the observed EPR spectral parameters (Table 1).

With the aim of confirming the structure of **4** using ESI-MS and ESI-MS/MS techniques, the DBNBS radical adduct solution was injected directly into the mass spectrometer immediately after EPR analysis. Despite changing the parameters on the spectrometer,



Scheme 2. Proposed mechanism for the formation of DBNBS radical adduct **4**. In bold, the H and N atoms that interact with the unpaired electron spin.

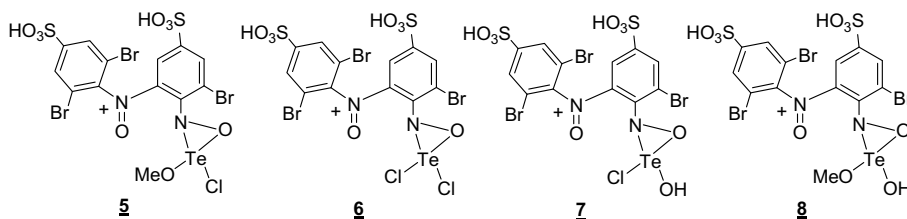


Fig. 2. Structures of DBNBS adducts based on the ions detected by ESI(+)-MS analysis.

the hypothetical adduct **4** could not be detected. On the other hand, DBNBS adducts with structures similar to **4** (Fig. 2) were detected by ESI-MS experiments in which the spectrometer was operated in the positive ion mode (ESI⁽⁺⁾-MS).

As shown in the expanded ESI⁽⁺⁾-MS spectra (Figs. 3 and 4), the ionic clusters of the detected species comprised two pairs of DBNBS adducts (**5/6** and **7/8**, respectively) in which different groups were linked to the Te atom. The exchange of Cl for OMe

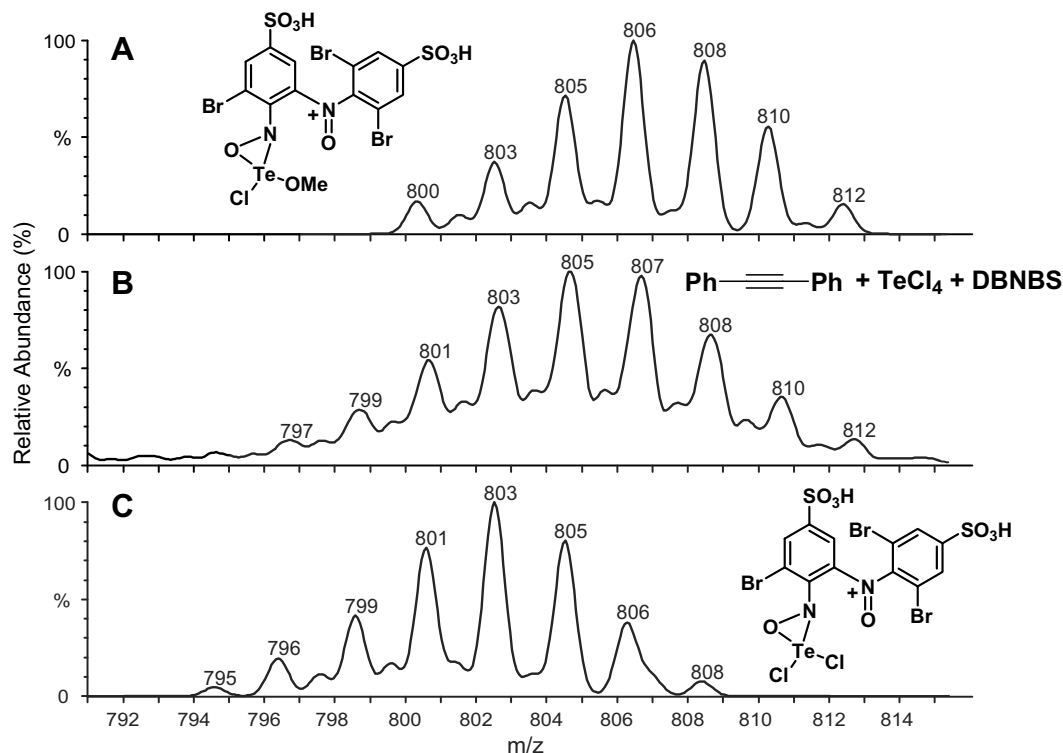


Fig. 3. Recorded ESI⁽⁺⁾-MS and simulated mass spectra of the cluster centered on m/z 805. (A) Simulated spectrum for compound **5** (molecular formula $C_{13}H_9Br_3N_2S_2O_9TeCl$). (B) Experimental spectrum. (C) Simulated spectrum for compound **6** (molecular formula $C_{12}H_6Br_3N_2S_2O_8TeCl_2$).

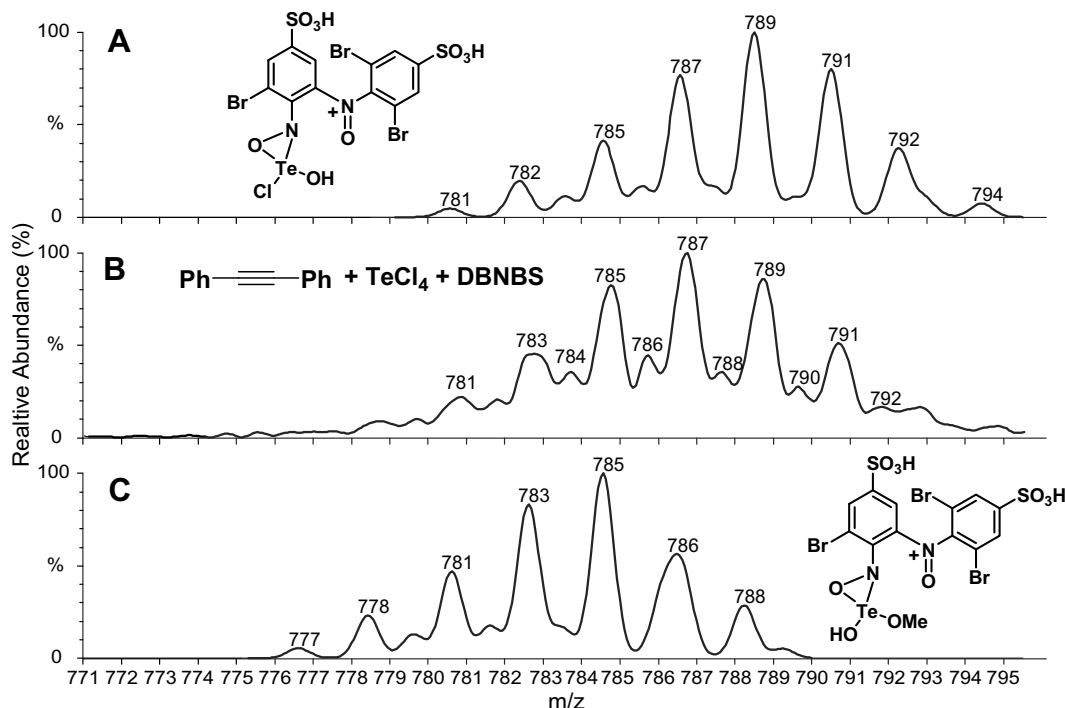


Fig. 4. Recorded ESI⁽⁺⁾-MS and simulated mass spectra of the cluster centered on m/z 787. (A) Simulated spectrum for compound **7** (molecular formula $C_{12}H_7Br_3N_2S_2O_9TeCl$). (B) Experimental spectrum. (C) Simulated spectrum for compound **8** (molecular formula $C_{13}H_{10}Br_3N_2S_2O_{10}Te$).

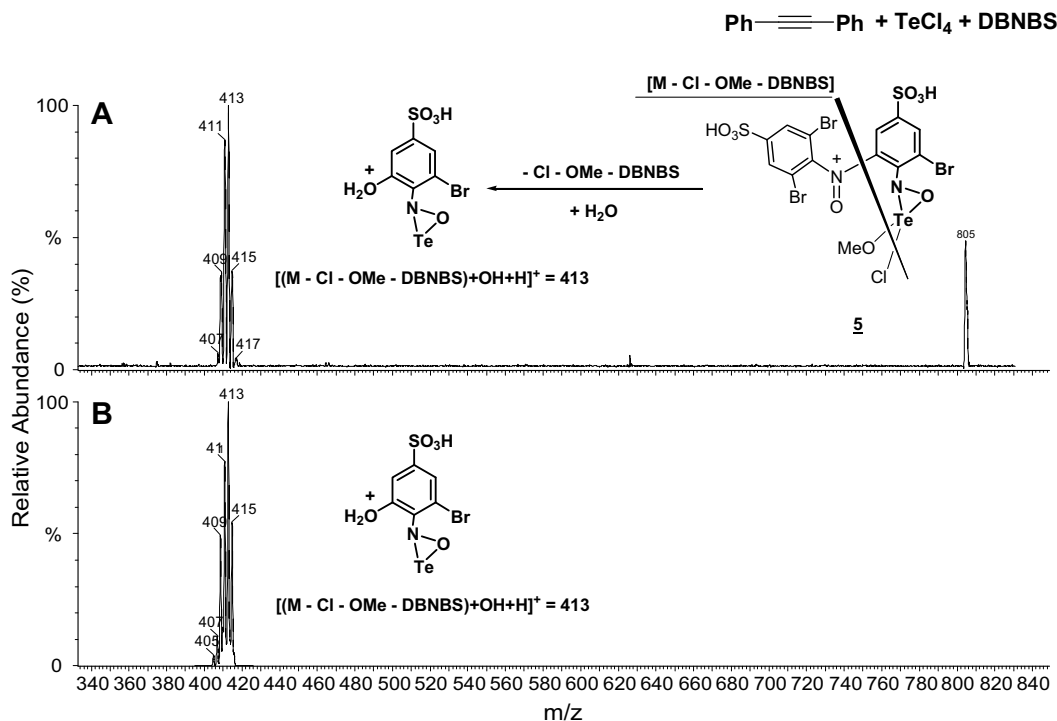
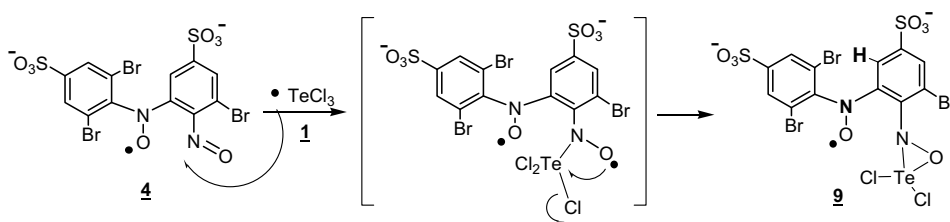


Fig. 5. Recorded ESI⁽⁺⁾-MS and simulated mass spectra of the ion at m/z 804. (A) Experimental spectrum of **5**. (B) Simulated spectrum for compound with molecular formula $\text{C}_6\text{H}_5\text{BrNSO}_5\text{Te}$.

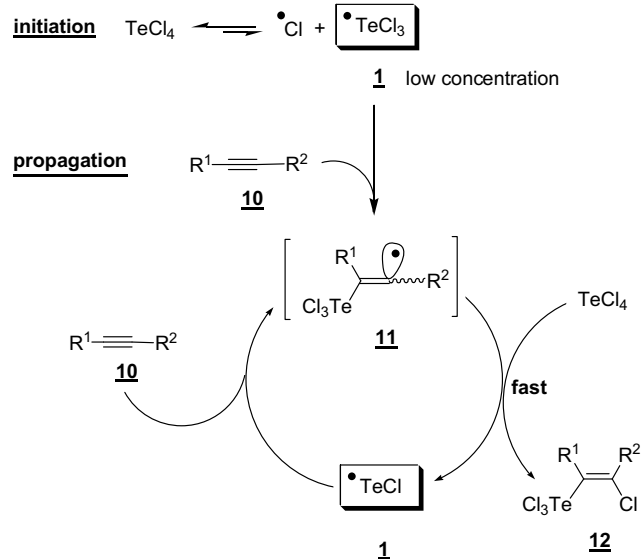


Scheme 3. Proposed mechanism for the formation of EPR-active radical adduct **9**. In bold, the H and N atoms that interact with the unpaired electron spin.

or OH groups linked to Te would have occurred during the course of ESI-MS analysis [20]. As can be observed, the isotopic distribution patterns of the recorded mass spectra (Figs. 3 and 4, spectra B) are analogous to the simulated spectra (Figs. 3 and 4, spectra A and C).

ESI-MS/MS of the ion at m/z 805 from the DBNBS adduct **5** (Fig. 5A) showed a cluster of ions at m/z 407, 409, 411, 413 and 415, corresponding to the fragment ions formed by the loss of the DBNBS group and transformation of Te(IV) to Te(II) with loss of the Cl and OMe groups and addition of H_2O to the aromatic ring ($[\text{M}-\text{Cl}-\text{OMe}] + \text{H}_2\text{O}$)⁺. These fragment ions show an isotopic distribution analogous to that of the simulated ESI-MS spectrum (Fig. 5B), which is characteristic of a compound containing one Br and one Te atom. The ESI-MS/MS of the DBNBS adducts **6–8** generated similar clusters of ions with the most abundant isotope ion at m/z 413.

On the basis of the results presented herein, the proposed mechanism involving the generation of **4** (Scheme 2) constitutes the initial step in the formation of the EPR-active radical adduct **9** (Scheme 3). Once formed, the nitroso group of **4** will be attacked by the radical specie **1** producing the DBNBS radical adduct **9**, reduction of which would give rise to the products **5–8** (Fig. 2) that were detected in ESI⁽⁺⁾-MS experiments.



Scheme 4. Reformulated mechanism for the addition reaction of TeCl_4 to alkynes.

Reaction mechanism: A radical chain mechanism (as outlined in Scheme 4) for the addition of TeCl_4 to alkynes is consistent with the evidence obtained in the present study. In the absence of an alkyne, the concentration of $\cdot\text{TeCl}_3$ radical **1** is probably too low to promote the formation of the DBNBS radical adduct **9** (Scheme 3), as has been demonstrated in control experiments. Chain propagation commences after addition of an alkyne **10** to the reaction mixture and the concentration of **1** increases. In the next step, **1** attacks the triple bond of **10** forming the undetectable vinylic radical intermediate **11** [21,22], which subsequently abstracts a Cl atom from a second molecule of TeCl_4 forming the vinylic telluride **12**, regenerating the Te-centered radical **1**, and thus continuing the cycle. Termination could be a consequence of the total consumption of the starting alkyne **10** or of the hydrolysis of TeCl_4 . The proposed structure of the DBNBS radical adduct **9** is in agreement with the observed EPR spectral parameters (Table 1).

In summary, the experimental evidence suggests that the addition of TeCl_4 to alkynes proceeds via a radical chain mechanism involving a Te(IV)-centered radical, the existence of which has been indirectly demonstrated for the first time in the present study.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at [doi:10.1016/j.jorganchem.2008.08.036](https://doi.org/10.1016/j.jorganchem.2008.08.036).

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