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Nitro and nitroso transformations in superacids

Kenneth K. Laali *

Department of Chemistry, Kent State University, Kent, OH 44242, USA

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Contents

Abstract

Novel transformations involving the nitro and nitroso groups in superacid media are discussed and summarized. NO_2-diprotonation is a key reaction for nitro PAHs, forming *N*,*N*-dihydroxyiminium–arenium dications whereas nitrosoarenes are *N*,*O*-diprotonated to form hydroxyiminium–arenium dications. In nitropyrenes a facile cyclization involving the nitro group leads to five- and/or six-membered ring heterocyclic cations. Nitro cyclization also occurs in nitroalkylbenzenes but at higher temperatures. Multinuclear NMR data for the resulting persistent NO_2-diprotonated dications and their cyclized analogs are gathered

* Tel.: +1-330-6722988; fax: +1-330-6723816.
E-mail address: klaali@kent.edu (K.K. Laali).

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and the structural requirements to bring about nitro cyclization are assessed. Conjugated nitroalkenes such as nitrostyrene and nitroethene are NO_2-diprotonated to form hydroxyiminium–carbenium dications. β-Heteroatom-substituted nitroethylenes are *C*,*O*-diprotonated and subsequently form hydroxynitrilium ions. Nitronate salts and unsubstituted nitroalkanes are activated in superacids via their protonated nitronic acid. β-ethoxycarbonyl-substituted nitroalkanes are activated via the *O*,*O*-diprotonated *aci*-nitro species with further *O*-protonation to give dioxonium–carbenium trications or via hydroxynitrilium ions. The NMR characteristics for the dihydroxyiminium–carbenium dications and hydroxynitrilium ions from various 2-nitroalkenes and their nucleophile quenching-derived cations are also gathered. The mechanistic aspects emphasizing dicationic (and tricationic) intermediates, their interplay and the potential synthetic benefits of these transformations which greatly extend the chemistry of the nitro group are highlighted.

Keywords: Nitro transformations; Nitroso transformations; Superacids

1. Introduction

Nitro compounds continue to play a pivotal role in many aspects of synthetic and mechanistic chemistry. In addition to being extremely valuable synthons in organic functional group transformations [1–5], certain nitroarenes as well as cyclic and acylic aliphatic nitro compounds have gained increasing importance as energetic materials [6]. As mutagenic environmental pollutants nitro-PAHs are the subject of considerable attention not only synthetically but also in structure/bioactivity relationships [7,8]. Strategies for NO_2 introduction and development of new, more effective, nitro group carriers especially via electrophilic chemistry and the mechanism of these reactions have contributed greatly to physical organic chemistry [9].

Aromatic and aliphatic nitroso compounds are important in their own right as organic intermediates [1–4], in relation to their biological activity [10] and in connection to the nitrosation mechanism [11].

The objective of this review is to discuss and summarize some novel chemistry involving the nitro group in superacid media, focusing on NO_2 diprotonation in conjugated and non-conjugated systems. For comparison, the behavior of the related aryl(alkyl)nitroso compounds which are *N*,*O*-diprotonated in superacids and their relationship to the intermediates formed via NO_2-diprotonation are examined. Trapping experiments with benzene and substituted benzenes have provided facile one-pot reactions leading to various oximes from nitro compounds and aminobiphenyls via the nitroso derivatives.

The reactive intermediates formed by dissolving nitro and nitroso compounds in protic superacids are amenable to direct studies by multinuclear NMR techniques (^1H, ^{13}C, ^{15}N).

Various liquid superacids (i.e. FSO_3H, HF, CF_3SO_3H as well as $FSO_3H{\cdot}SbF_5$ mixtures) have been utilized for direct observation of the resulting intermediates.

Among them CF_3SO_3H 'TfOH' is most frequently used as a preferred medium since it is sufficiently acidic (H_o) to bring about the required transformations while at the same time providing a much less oxidizing environment where typical side reactions (fluorosulfonation, sulfonation, possibly even fluorination depending on the substrate) are avoided. Superacid protonations of β-nitrostyrene, β-nitroethylene and its α-heteroatom-substituted derivatives as well as nitronate salts, nitroalkanes and α-carbonyl-substituted derivatives provide direct access to dications and hydroxynitrilium ions whose trapping reactions with nucleophiles give access to a variety of interesting cationic intermediates having the hydroxyiminium group. The chemistry of the nitro group is therefore greatly expanded in superacidic media.

2. Early advances

Following the early studies of nitro protonation in sulfuric acid by Deno [12], seminal direct studies by Hogeveen [13] and by Olah et al. [14] on protonation and Lewis acid complexation of nitro compounds and the NMR studies of the resulting intermediates laid the foundation for subsequent more recent investigations. Summaries of these contributions were given in 'Onium Ions' as part of an extensive chapter on azonium ions [15]. Earlier progress is therefore briefly reviewed here in order to set the stage for subsequent discussion.

Whereas at room temperature (r.t.), RNO_2 (R = Me, Et, *i*-Pr) and $PhNO_2$ are not fully protonated in sulfuric acid–oleum mixtures [12], in higher acidity superacids ($HF{\cdot}SbF_5$ HF–BF_3) they are O-protonated at low temperature to give static hydroxy-nitronium ion RNO_2H^+ [13,14] (Fig. 1).

Hydroxynitronium ions are classical cations as concluded in Hogeveen's low temperature IR studies [13]. Several examples of persistent hydroxy-nitronium cations have been provided by Olah and asssociates from suitable RNO_2 precursors, and their NMR characteristics have been discussed [14]. In general, the OH resonances are observed between 16.8 and 17.5 ppm.

Apart from *O*-protonation, nitro group can be *O*-alkylated using potent reagents such as $MeF–SbF_5$ in SO_2 solvent to form methoxynitronium ions [14a]. This can be achieved with both RNO_2 and $PhNO_2$ compounds. Finally, formation of persistent donor-acceptor complexes can be realized by nitro-coordination to Lewis superacids (typically BF_3 and SbF_5) [14a].

Variation in $\Delta\delta^{13}C$ and the overall NMR characteristics of the resulting species are consistent with *O*-alkylation and *O*-complexation at the nitro group (Fig. 2).

In $PhNO_2H^+$ magnetic equivalence and non-equivalence of the *ortho* protons depends on the rate of rotation of the NO_2H^+ group as a function of temperature which itself depends on the iminium character of the CN bond. An additional process involves intramolecular proton exchange via a symmetrical transition state.

$$RNO_2 \xrightarrow{\text{superacid}} RNO_2H^+$$

Fig. 1.

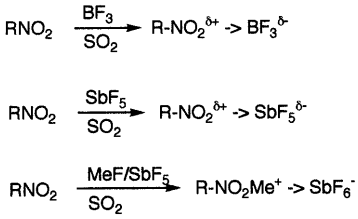


Fig. 2.

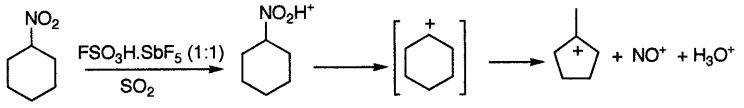


Fig. 3.

These arguments were addressed by dynamic ^{1}H-NMR and the coalescence temperatures as a function of substituents, and via line shape analysis to obtain activation barriers for NO_2H^+ rotation [14b].

An interesting discovery by Olah et al. [14b] was that suitable aliphatic hydroxynitronium ions undergo denitration to form persistent carbocations (Fig. 3).

Low temperature protonation of nitrosocyclohexane led to the observation of *N*-protonated cyclohexanone oxime (*N*,*O*-diprotonation) together with methylcyclopentyl cation [14b] (Fig. 4).

3. An overview of the intermediates accessible by protonation of nitro and nitroso groups in superacids

Superacid media provide a unique environment for generation of dications from nitro and nitroso compounds. In lower acidity systems such as in H_2SO_4 dications are at best involved in rapid equilibria and thus can not be exploited. Depending on the choice of precursor, the following intermediates are accessible via nitro and nitroso diprotonation: (a) *N*,*N*-dihydoxy-iminium–arenium or *N*,*N*-oxo-iminium–arenium dications via nitro-PAHs (Fig. 5); (b) *N*,*N*-dihydroxyiminium–carbenium dications from conjugated nitro compounds such as β-nitrostyrene (Fig. 6); (c) *N*,*N*-dihydroxyiminium and hydroxynitrilium cations via nitroalkanes or nitronate anions (Fig. 7); (d) hydroxynitrilium ions or trications from ethylnitroacetate or α-nitroacetophenone Fig. 8; (e) iminium–benzenium–dications from nitroso, azo,

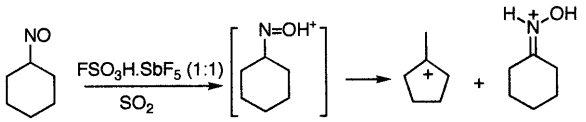


Fig. 4.

azoxy, nitrobenzene and from PhNHOH (Fig. 9); (f) oxonium–iminium dications from *p*-OH–PhNO and *p*-OMe–PhNO and from benzoquinone monooximes (Fig. 10); (g) hydroxyiminium–arenium dications from PAH–NO (Fig. 11); (h) *C*,*O*-diprotonated 1-amino-2-nitroethene derivatives which are transformed into hydroxynitrilium ion (Fig. 12).

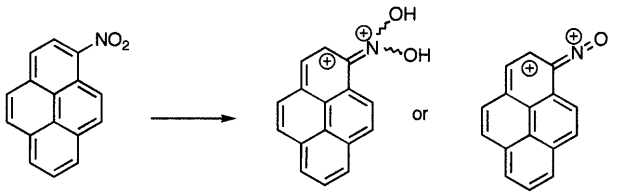


Fig. 5.

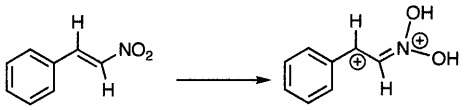


Fig. 6.

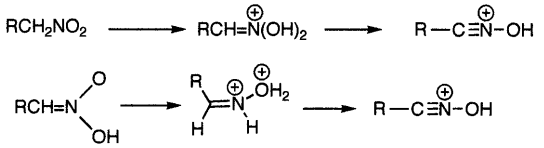


Fig. 7.

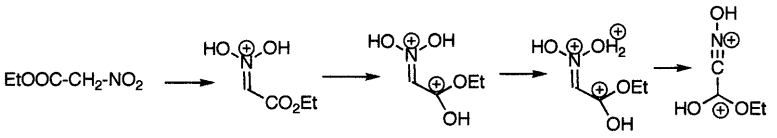
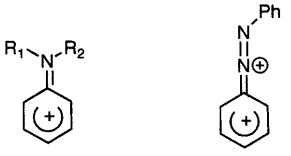


Fig. 8.



$R_1 = H, R_2 = OH$

$R_1 = H, R_2 = NHPh$

$R_1 = R_2 = H$

Fig. 9.

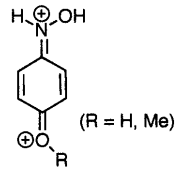


Fig. 10.

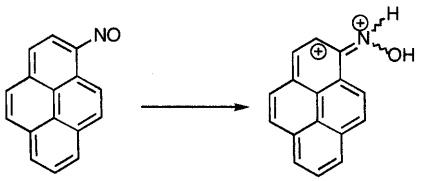


Fig. 11.

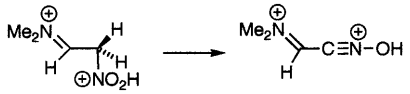


Fig. 12.

4. Nitro group diprotonation and cyclization in nitroarenes

Based on cryoscopic measurements Shudo et al. [16] concluded that 1-nitronaphthalene is NO_2-diprotonated in TfOH to give *N*,*N*-dihydroxyiminium–naphthalenium dication. Formation of an oxo-iminium–naphthalenium dication was excluded based on quenching experiment with H_2O^{18} whereby no O^{18} incorporation into the recovered nitronaphthalene was found. The isomeric 2-nitronaphthalene was similarly suggested to be NO_2-diprotonated (Fig. 13).

Ridd and associates [17] discovered that when nitroalkylbenzenes are heated in TfOH they undergo two types of transformation, namely 1,3-nitro group rearrangement and nitro cyclization (Fig. 14).

Presence of one *ortho* ethyl group led only to nitro cyclization to form anthranil, but with two *ortho* ethyl groups cyclization and nitro rearrangement became competitive. Replacing ethyl groups for methyl as in 1,3-dimethyl-2-nitrobenzene resulted in rearrangement and no cyclization.

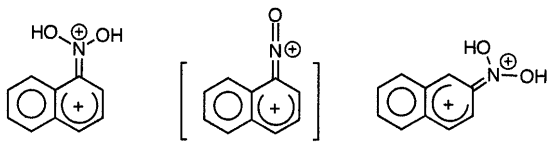


Fig. 13.

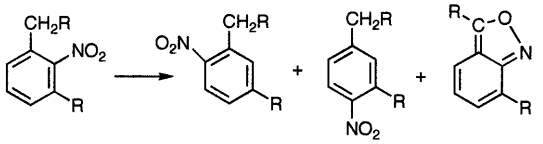


Fig. 14.

It was suggested that whereas rearrangement can occur via the benzenium ion of *ipso* attack with relief of steric crowding as the driving force, cyclization occurs via the *aci*-form of the nitro compound. Superacidity is therefore a requirement to produce an equilibrium concentration of the *aci*-form which can lead to nitro cyclization (Fig. 15).

Subsequent work by Ridd et al. [18] showed that increasing steric crowding facilitates nitro cyclization so that with R = *i*-Pr cyclization occurres at r.t. in TfOH. Nitro group rearrangement accompanying these cyclizations was probed via kinetic studies and labeling experiments and suggested to be intramolecular.

Based on additional studies [19] it was proposed that nitro cyclization in 2-nitroethyl-benzene does not proceed via the *aci*-nitro form but via a concerted [1,5]sigmatropic shift of hydrogen from the α-side chain to the protonated nitro group (Fig. 16).

When 2-nitrobenzyl alcohol was heated in TfOH to 90°C, 4-amino-3-carboxyphenyl triflate was isolated in 66% yield [20]. The same compound was formed by heating 2-nitrobenzyl chloride or 2-nitrosobenzaldehyde in TfOH. It was proposed that the amino derivative is produced from the nitro-cyclized intermediate according the scheme below, where nitro group acts as internal nucleophile (Fig. 17).

2-Chloro-1,3-dimethylbenzene reacts with *p*-dinitrobenzene in hot TfOH to give the corresponding triarylmethyl carbinol and *p*-diaminobenzene [21]. It was proposed that triaryl methyl cation is formed via an initial hydride transfer from 2-chloro-1,3-dimethylbenzene to the protonated nitrobenzene forming a benzyl cation which undergoes benzylation, debenzylation/rebenzylation steps followed by oxidation to give the corresponding trityl carbocation. The ability of protonated

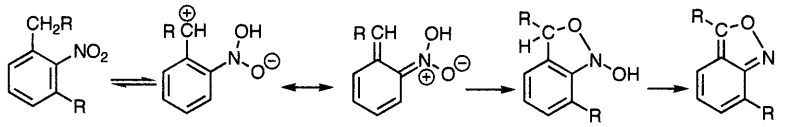


Fig. 15.

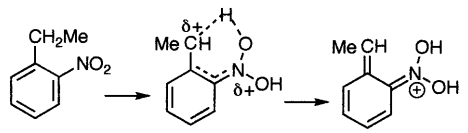


Fig. 16.

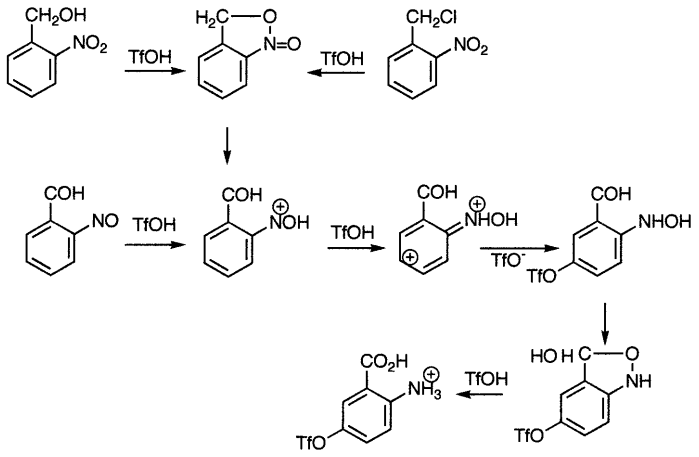


Fig. 17.

nitro group to abstract hydride ion from benzylic position (s) and nitro reduction in superacidic media were considered to be the key mechanistic features (Fig. 18).

Laali and associates [22] studied a series of sterically crowded mono- and dinitro-alkyl (cycloalkyl)pyrenes possessing buttressed nitro groups at low temperature in superacid media (FSO_3H, TfOH or $FSO_3H.SbF_5$ (4:1)) (Fig. 19).

Nitro group diprotonation occurred in all cases to give *N*,*N*-dihyoxyiminium–pyrenium dications. Although possible formation of oxo-iminium–pyrenium dications could not be ruled out, based on symmetry considerations in the isopropyl groups in the NMR spectra, dihydroxyiminium–pyrenium dication formation was suggested to be more probable. A facile nitro cyclization occurred with dications having an *ortho* or *peri* isopropyl group or a *peri*-cyclohexyl group, whereas no

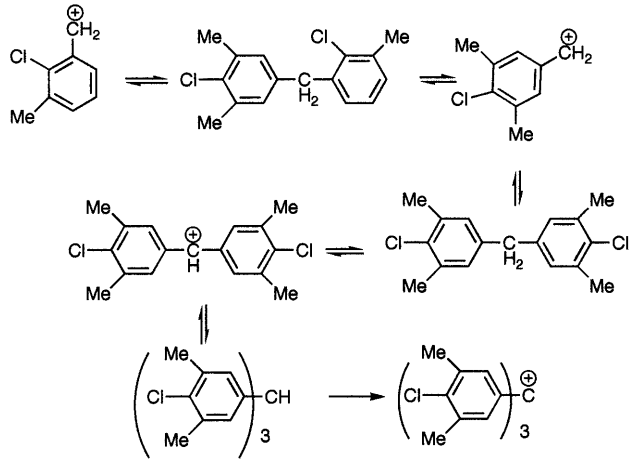


Fig. 18.

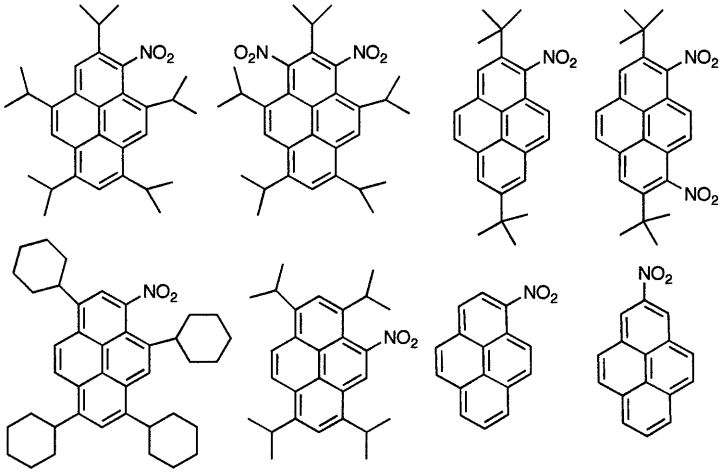

NO2
O2N
NO2
NO2
NO2
NO2
NO2
NO2
NO2
NO2

Fig. 19.

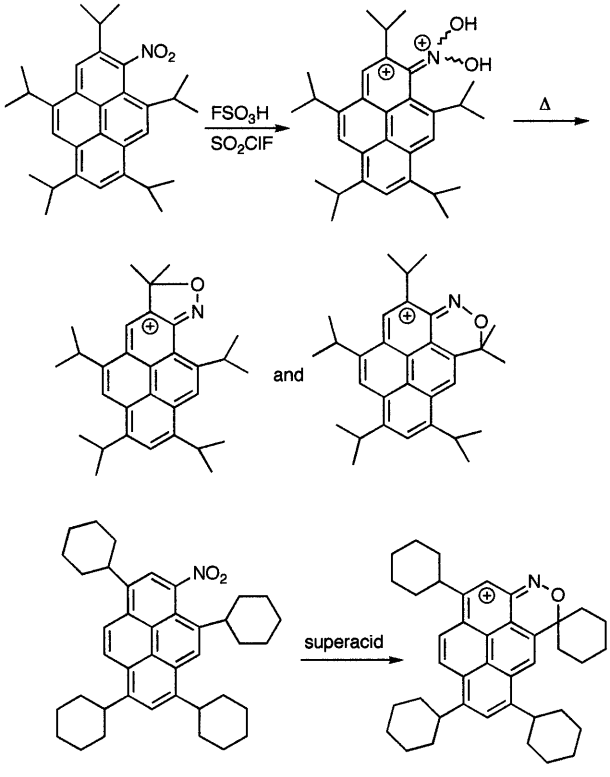

NO2
FSO3H
SO2ClF
OH
N
OH
Δ
O
N
and
N
O
NO2
superacid
N
O

Fig. 20.

cyclization could be induced with *ortho* *t*-Bu groups. The resulting five-membered ring oxazoline fused and six-membered ring oxazine-fused cations were studied directly by NMR. *Ortho* cyclization leading to five-membered ring was more facile than *peri*-cyclization to give a six-membered ring heterocycle (Fig. 20).

These studies demonstrate that the presence of at least one benzylic C*H* group is a requirement for the cyclization to proceed. In line with the earlier proposal by Ridd on anthranil formation [17] the following mechanism was suggested (Fig. 21).

Parent 1-nitropyrene is NO_2 diprotonated in $FSO_3H{\cdot}SbF_5$ (1:1) to give a dihydoxy-iminium–pyrenium dication whereas 2-nitropyrene is ring protonated [22,23].

2,4,6,8,10-Pentaisopropylpyrene reacts with NO_2^+ BF_4^- in CD_3CN to give a mixture of two cations namely the σ-complex of nitration and the *N*,*N*-dihyroxyiminium–pyrenium dication [23].

It was suggested that the former was the precursor to the cyclized cation in line with the overall mechanistic picture and earlier suggestions by Ridd with 2-ni-

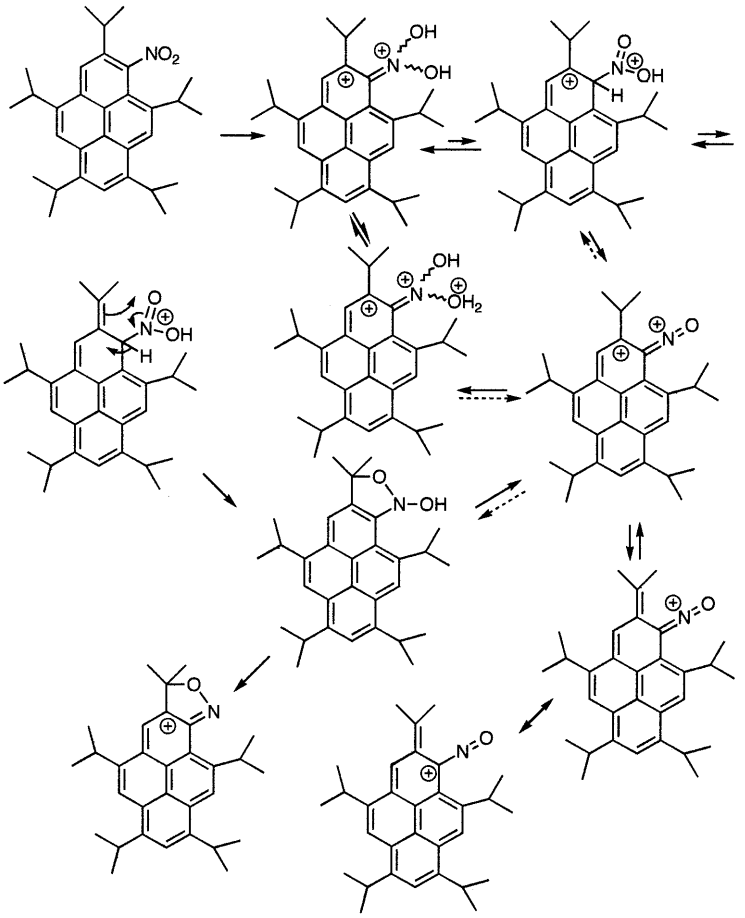


Fig. 21.

troethylbenzene in TfOH [17]. The driving force for nitro group diprotonation in crowded nitroarenes is believed to be steric inhibition to delocalization (nitro group twisting).

An interesting observation was that quenching of the cyclized cation via 2-nitro-penta-isopropylpyrene with water gave a green solid which was paramagnetic. Based on NMR, mass spectrum and elemental analysis the paramagnetic component was identified as a nitrosonium radical cation salt (fluorosulfate) whose formation as a minor product originated from the cyclized cation via ring opening, reduction and protonation (Fig. 22).

In further studies, Laali and Hansen [24] found that low tempertature protonation of 1-nitropyrene and its N-15 isotopomer with 1:1 $FSO_3H{\cdot}SbF_5$–SO_2ClF (or

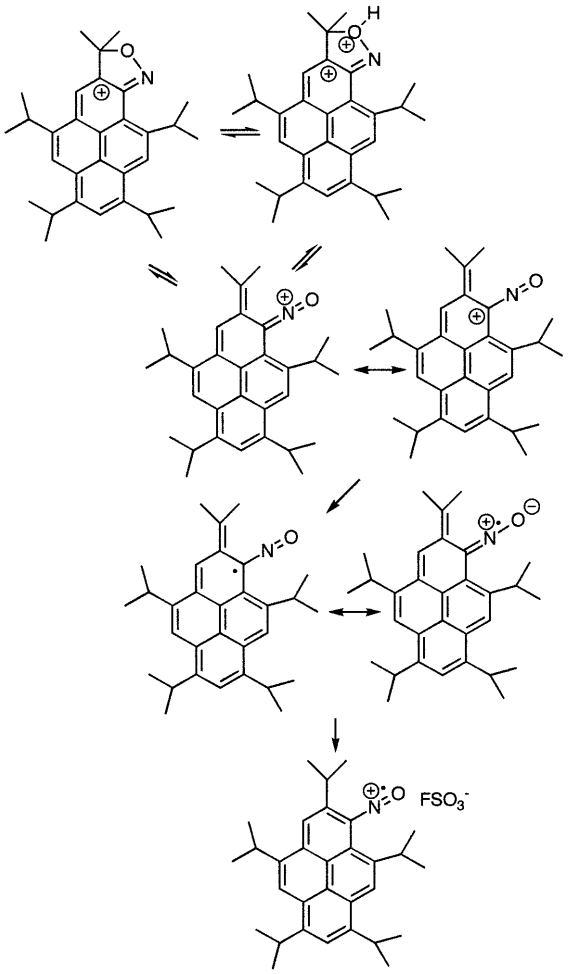


Fig. 22.

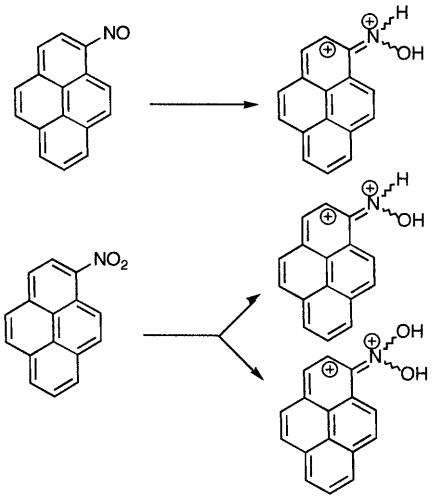


Fig. 23.

SO_2) or with 4:1 $FSO_3H{\cdot}SbF_5$–SO_2ClF gives either dihydroxyiminium–pyrenium dication $Ar{=}NO_2H_2^{+2}$ or the hydroxyiminium–pyrenium dication $Ar{=}NHOH^{+2}$ as the principle NMR observable persistent species whose formation depends on sample concentration, reaction time and the superacid.

The hydroxyiminium–pyrenium dication was independently generated from authentic nitrosopyrene (Fig. 23).

The geometrical features of the $=NH(OH)^{2+}$ and $=N(OH)_2^{2+}$ dications have been probed by PM3 calculations [24].

5. Superacid protonation of nitrosobenzene and its derivatives

Protonation of nitrosobenzene is important in regard to the extent of nitrenium ion character. An iminium–benzenium dication intermediate was proposed by Okamoto et al. [25] in the reaction of nitrosobenzene with benzene in TfOH forming 4- and 2-aminobiphenyls and amino-terphenyls as products. Related intermediates were postulated in phenylation of azo and azoxy compounds [25] (Fig. 24).

Interestingly, the same type of products (albeit in lower yields) were isolated from the reaction of nitrobenzene with benzene after heating in TfOH. These could arise from dihydroxy-iminium–benzenium dication as the initial intermediate or by nitro reduction forming hydroxy-iminium-benzenium dication. An iminium–benzenium dication intermediate (or protonated nitrenium ion) was also postulated by Okamoto et al. [26] in reaction between arylhydroxylamine and benzene in TfOH (Fig. 25).

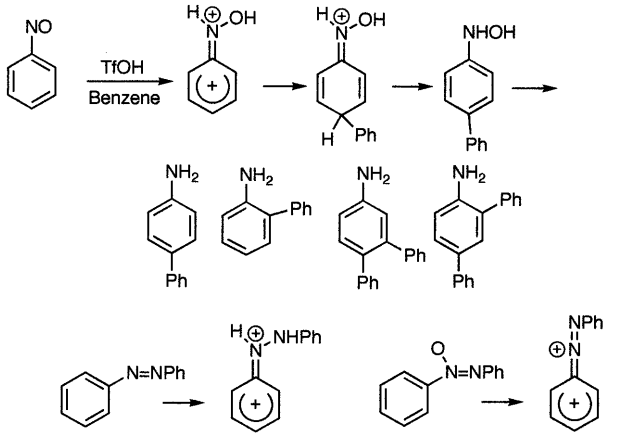


Fig. 24.

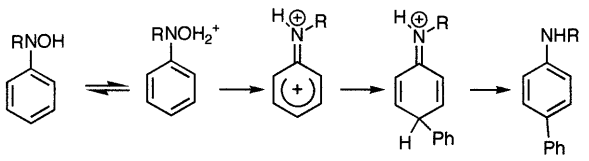


Fig. 25.

Olah and Donovan [27] demonstrated that parent PhNO and its *para*-substituted derivatives (such as 4-OMe, 4-NMe_2) are nitroso *N*,*O*-diprotonated in 1:1 $FSO_3H{\cdot}SbF_5$–SO_2 to form persistent dications. Similar dications can be generated starting with benzoquinone monooximes, whose NMR data in comparison with suitable models suggest that whereas the parent $PhNOH_2^{+2}$ can best be described as an iminium–benzenium dication the *para*-substituted derivatives are best viewed as iminium–oxonium dications. In both cases, there is little protonated nitrenium ion character (Fig. 26).

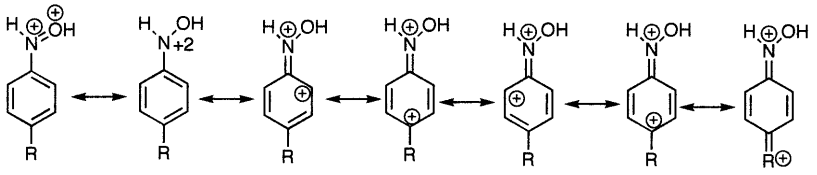


Fig. 26.

6. Nitrocyclization in α-cyclopropyl derivatives

In a series of papers, Russian workers reported on heterocyclic cations formation by nitro group cyclization [28–30]. Cyclizations were induced by protonation of an α-cyclopropyl group or a suitable alkene-substituent using FSO_3H or conc. H_2SO_4. Depending on the structure of the nitrobenzene derivative, the kinetic product(s) are either the *N*-oxobenzo[2,1]isoxazolinium (five-membered ring) or *N*-oxobenzo[2,1]oxazinium ions (six-membered ring) (Fig. 27).

With 2-methylcyclopropanes, six-membered ring cations isomerized to 5-membered ring ions forming an equilibrium mixture of the four possible cyclic cations [29] (Fig. 28).

Protonation of *o*-nitrophenylcyclopropane with H_2SO_4 followed by quenching with water gave the *o*-nitrosoketone derivative. Protonation in TFAH led instead to direct capture of the initially formed carbocation and no nitroso product was obtained [30] (Fig. 29).

Shudo and co-workers later reexamined nitro group cyclization in 2-cyclopropyl-nitrobenzene in TfOH [31]. Quenching with H_2O under these conditions gave the nitroso ketone derivative. A similar model cyclization involving a bromide derivative which was ionized with AgOTf and its trapping with benzene were also reported (Fig. 30).

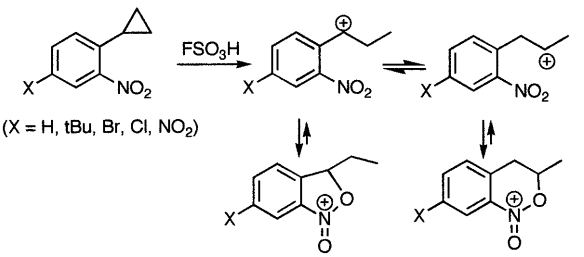


Fig. 27.

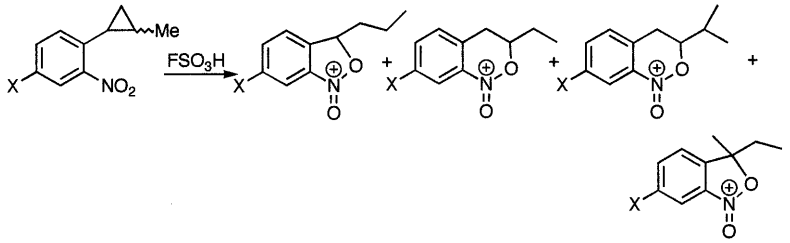


Fig. 28.

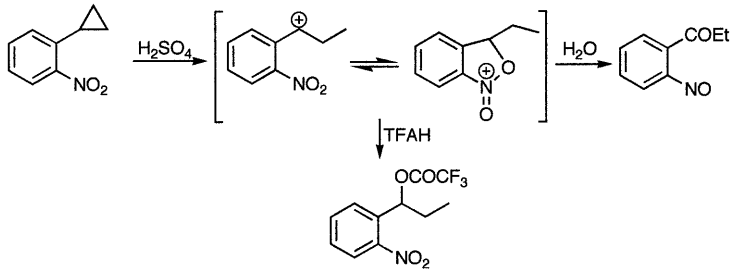


Fig. 29.

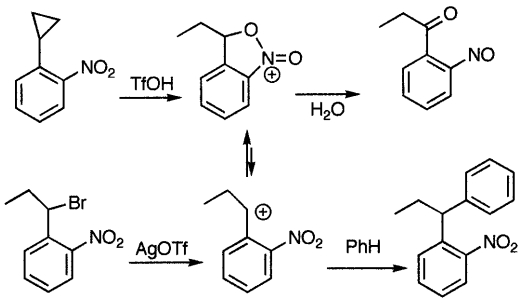


Fig. 30.

7. NMR data on persistent cations derived from nitro and nitroso arenes

To facilitate comparison, in this section the available multinuclear NMR data on a number of persistent cations derived from nitro and nitroso aromatics are gathered in Chart 1 and some of their key features are highlighted.

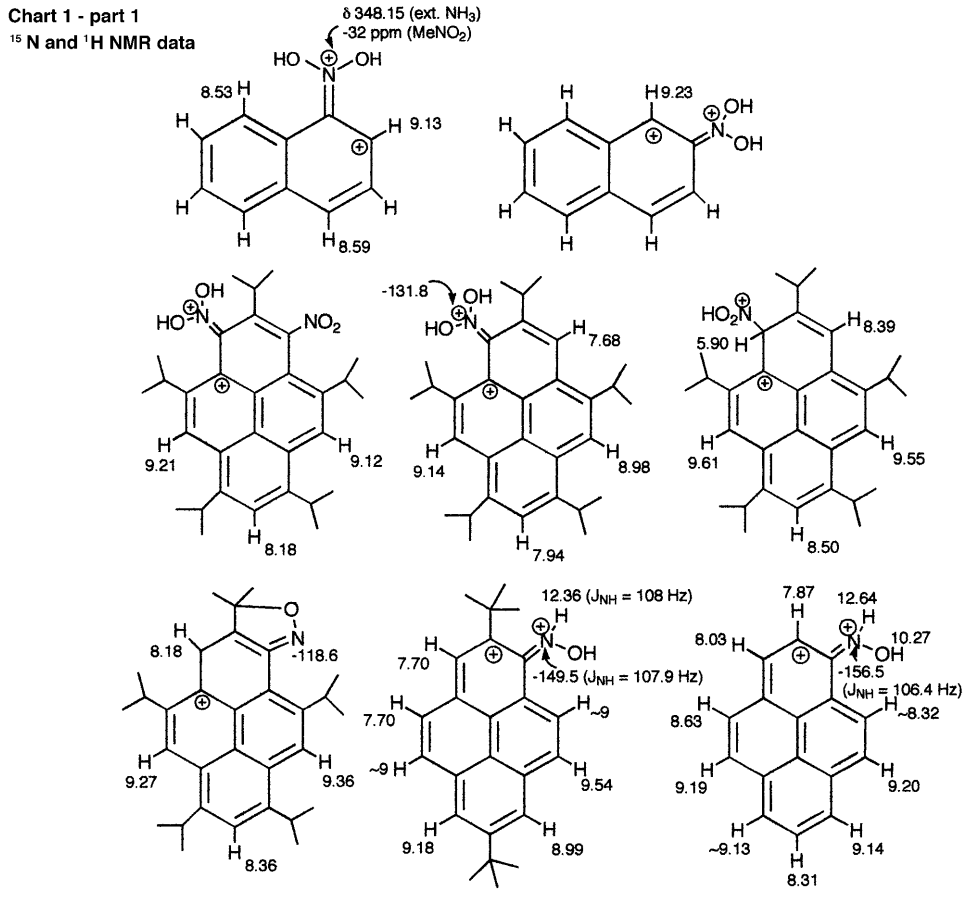


Chart 1 - part 2

^{13}C NMR data($\Delta\delta$ values in parenthesis)

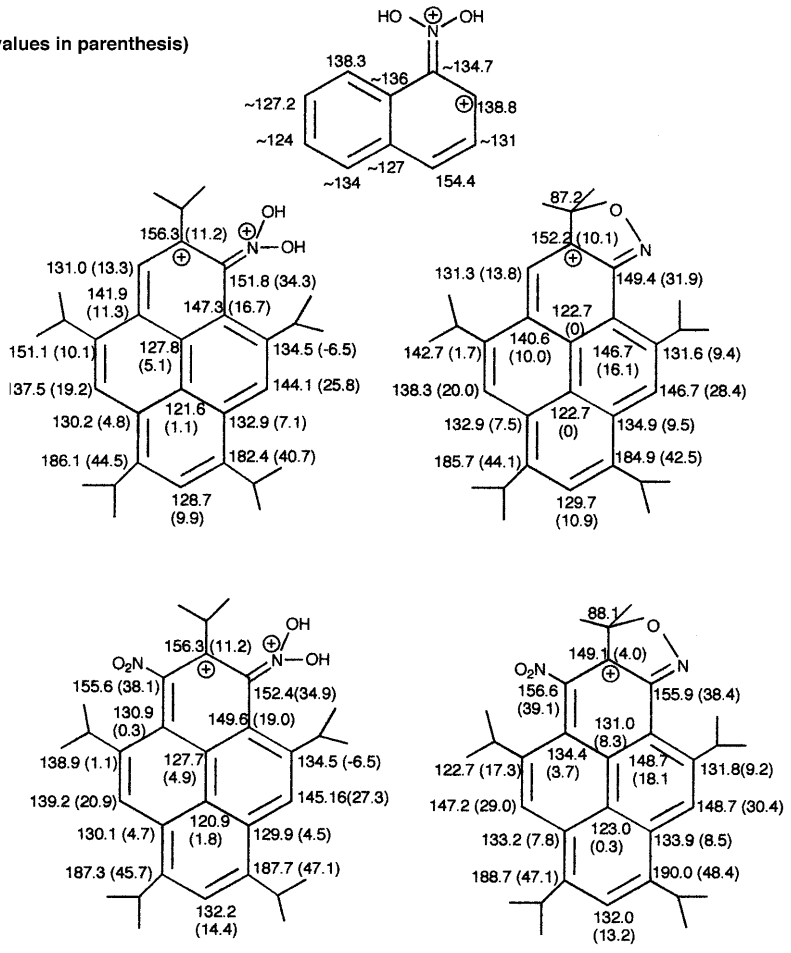


Chart 1 - part 3
(multinuclear NMR data)

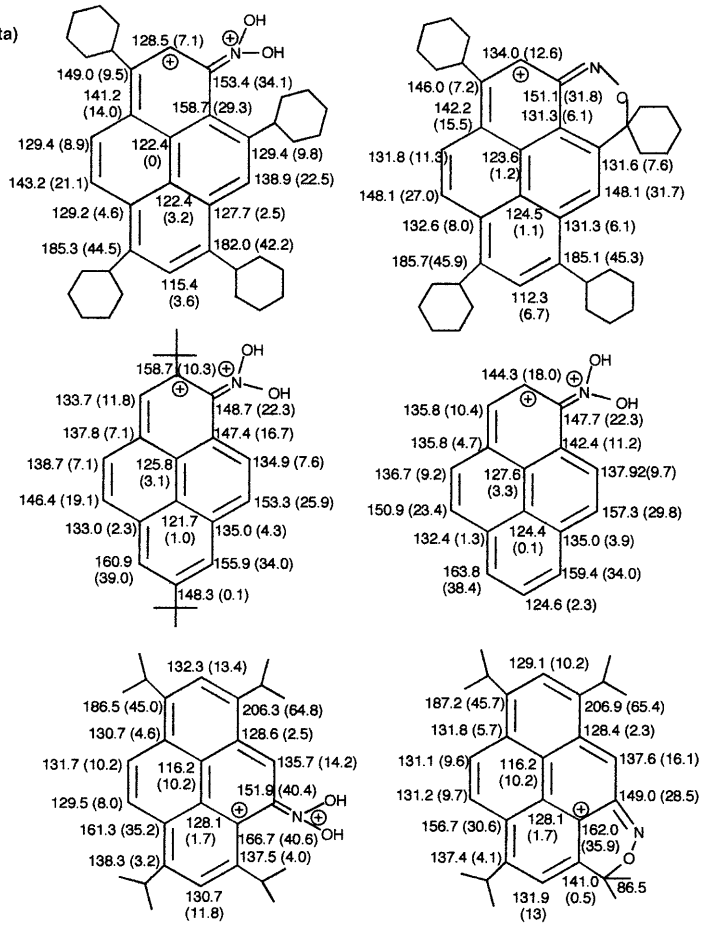
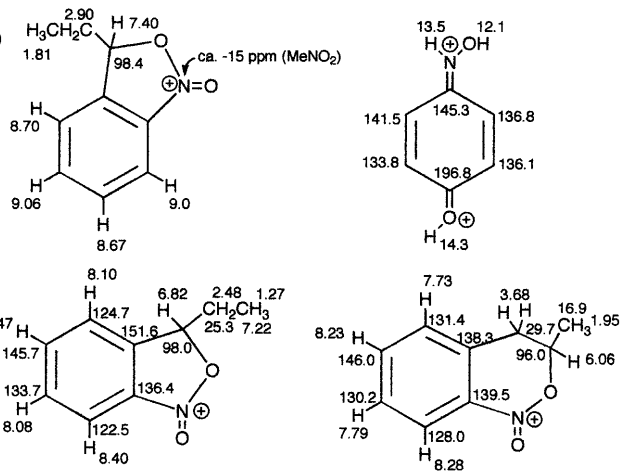


Chart 1 - part 4
(multinuclear NMR data)



The ^{15}N-NMR shift for PAH=NHOH and PAH=N(OH)$_2$ dications are relatively close showing that the effect of extra oxygen is small. They fall in the general range for iminium ions. These ^{15}N shifts are quite different from the value reported for NO_2-diprotonted nitronaphthalene.

The ^{15}N shift for the dication derived from sterically crowded 1-nitro-2,4,6,8,10-penta-isopropyl pyrene is a singlet at δ −131.8. Upon cyclization this resonance is replaced by the signal at δ −118.6. For *N*,*O*-diprotonated nitrosopyrene the ^{15}N shift is at δ −156.4 with the NH coupling of 106.4 Hz. In general, hydroxyiminium arenium dications are readily distinguished by the presence of a distinct low field N*H* resonance and from one-bond NH coupling. In the ^{13}C-NMR, the imminium carbon is in the 142–156 ppm range. Based on the magnitude of $\Delta\delta^{13}$C it is concluded that the charge is extensively delocalized within the pyrenium moiety similar to pyrenium ions of protonation. The onset of nitro cyclization in isopropylpyrenes is easily detectable in the ^{1}H-NMR by the appearance of a deshielded methyl singlet around 2 ppm concomitant with four new deshielded aromatic singlets. In the *N*,*O*-diprotonated *p*-hydroxynitrosobenezene, the imminium carbon is at δ 145.3 and the *para* carbon at δ 196.8. The N*HOH* and the *p*-O*H* resonances are clearly distinguished with the latter being the most deshielded. In *N*-oxobenzo[2,1]isoxazolinium and *N*-oxobenzo[2,1]oxazinium ions there is a large difference in the ^{13}C shift between the five- and six-membered ring analogs at one of the ring fusion carbons β to nitrogen.

8. Nitro cyclization without superacid

An interesting aspect of the chemistry of 4,6-dinitrobenzofuroxan DNBF is its highly electrophilic nature [32]. Terrier et al. [33] reported that DNBF reacts with indene to form initially the σ-zwitterionic adduct with the nitro group undergoing subsequent cyclization on the benzylic cation (Fig. 31).

In the context of the present review this reaction may be considered as a 'non-superacid' version of nitro cyclization. In earlier studies [34] a similar reaction between ethyl vinyl ether and DNBF resulting in nitro cyclization was considered to be concerted.

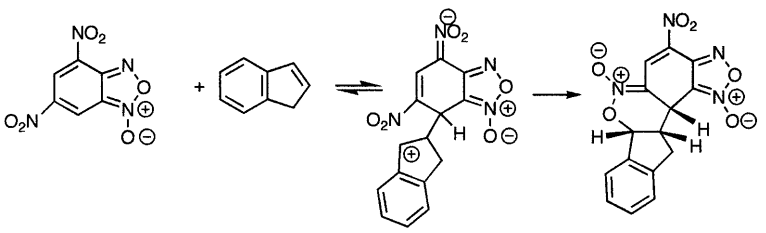


Fig. 31.

9. β-Nitrostyrene in superacid

On the basis of NMR studies and cryoscopic measurements Shudo et al. [35] concluded that β-nitrostyrene is *C*,*O*-diprotonated in TfOH to form the *N*,*N*-dihydroxyiminium-benzyl dication. Formation of the *O*,*C*-diprotonated dication was excluded. The *O*,*O*-diprotonated dication is represented by resonance hybrid forms a,b,c illustrating that approximately one positive charge resides on the benzyl moiety and one positive charge on the iminium nitrogen. The oxo-iminium structure was excluded based on cryoscopy and by quenching with H_2O^{18} (Fig. 32).

In related studies [36] trapping (with benzene) of the resulting dications formed from β-nitrostyrene and β-methyl-β-nitrostyrene and their *para* substituted derivatives in TfOH was examined. With β-nitrostyrene derivatives, diphenylacetophenoneoxime derivatives were formed whereas with β-methyl-β-nitrostyrenes a mixture of acetophenoneoxime and triphenylmethane resulted. The following generalized mechanism was proposed (Fig. 33).

This work was extended to nitroethylene [37] which was also shown to be diprotonated in TfOH to yield *N*,*N*-dihydoxyiminium methylium dication, isoelectronic with guanidinium cation (Fig. 34).

Based on ab initio calculations it was proposed that the intrinsic stability of the dication stems from Y-delocalization (the π-bond and two lone pairs from the OH groups).

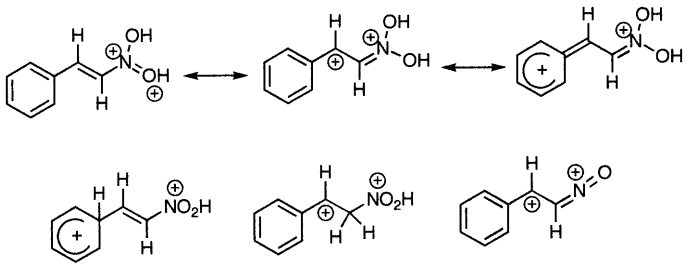


Fig. 32.

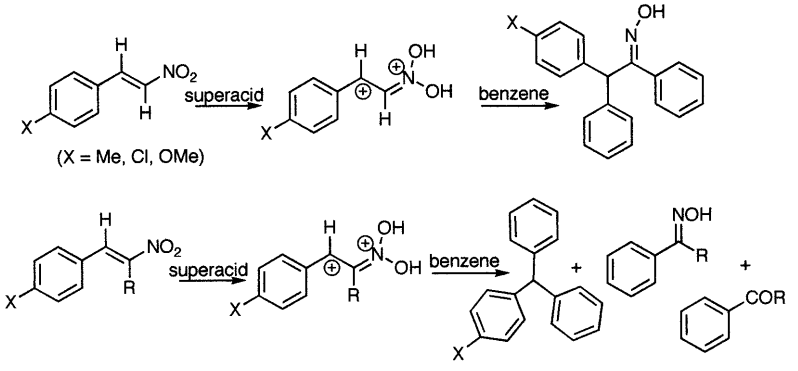


Fig. 33.

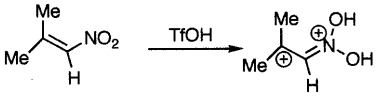


Fig. 34.

10. Nitroalkanes in superacid

Acid-catalyzed reactions of nitronic acids and nitronate salts with aromatics were studied independently by Jacquesy [38] and by Shudo [39] and their associates in various superacids (HF, $HF{\cdot}SbF_5$, TfOH) to give oximes (mostly *Z*-isomer) after quenching. Oxime formation also occurred in H_2SO_4 but in lower yield. These reactions are only catalyzed by superacids and do not proceed in TFAH which is acidic enough to protonate nitronic acid. The results argue in favor of an additional protonation to form an *O*,*O*-diprotonated *aci*-nitroalkane as a key step. Protonated nitronic acid and hydroxynitrilium cations were proposed as key intermediates whose nucleophilic trapping with ArH produces oximes (Fig. 35).

In follow-up studies [40] trapping of the hydroxynitrium ion with aromatics was investigated directly by NMR where the resulting *Z*/*E*-oximes are in situ protonated. The data indicate that under kinetic control the trapping product is the *Z*-oxime.

Superacid catalyzed reactions of ethyl nitroacetate with aromatics forming phenylated oximes were probed independently by Shudo [39] and by Coustard et al. [41]. In order to rationalize the observed *E*-stereochemistry in the oxime in which the entering aryl group and the OH are *cis*, Coustard et al. argued that formation of a hydroxynitrilium ion as the immediate precursor to the oxime would be more appropriate. It is known that in nitrilium ions under kinetic control the attacking nucleophile and the forming lone-pair are *trans* to each other [41] (Fig. 36).

Further studies have shown that arylated oximes can be directly synthesized from nitroalkanes in superacids with the *Z*-oximes being the primary products [41] (Fig. 37).

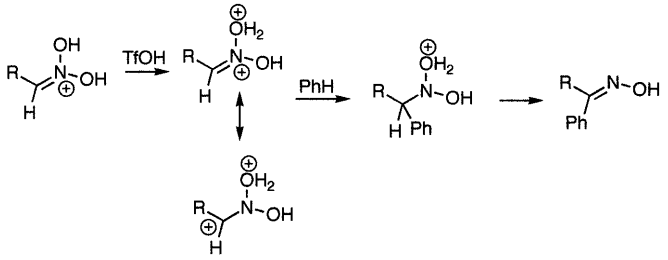


Fig. 35.

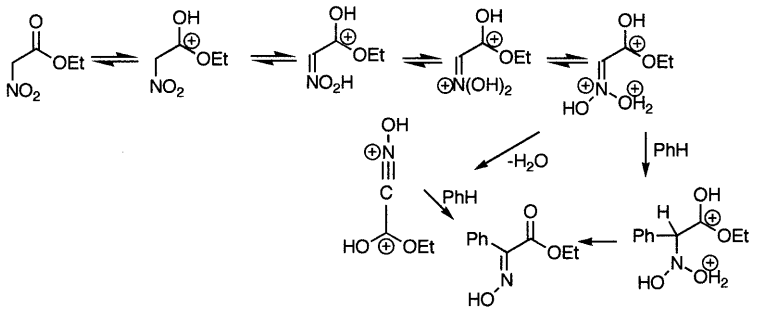


Fig. 36.

11. α-Heteroatom-substituted 2-nitroethylenes in superacids

In a series of papers Coustard examined the superacid protonation of α-amino-, α-thio-, 1,1-bis(methylthio)- and 1-arylamino-1-methylthio-2-nitroethylenes in $HF{\cdot}SbF_5$ and in TfOH [41–45]. It was shown that these compounds are *C,O*-diprotonated and are subsequently transformed into hydroxynitrilium ions which can be quenched with aromatics, MeS^- or MeO^- as nucelophiles, with the entering nucleophile and the OH in the *cis* orientation (Fig. 38).

In representative cases, the *syn* configuration (entering nucleophile and the OH group) has been proved via X-ray analysis of the resulting hydroxyimino derivatives [44].

1,1-bis-(methylthio)-2-nitroethylene forms a dication which is quenched in situ at the imminium carbon and undergoes a further nucleophilic quenching at the β-position on work-up to produce oximes. Quenching with MeOH leads to dimerization and furoxane formation [42].

Prolonged reactions or increasing sample temperature led to nucleophilic attack (F^- or TfO^-) at the iminium carbon (Fig. 39).

It was proposed that protonated nitronic acid is the precursor to hydroxynitrilium ion [42]. The mechanistic scheme shown below summarizes the formation of hydroxynitrilium cation and its subsequent transformations (Fig. 40).

Low temperature NMR monitoring showed that the initially formed *O,C*-diprotonated dications are predominantly the *Z* isomers. On increasing temperature, subsequent isomerization gives an *E*/*Z* mixture which are then slowly transformed into hydroxynitrium ions [43].

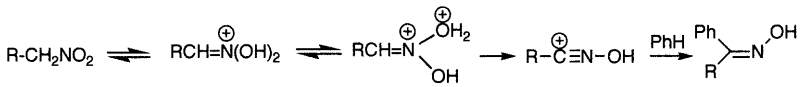


Fig. 37.

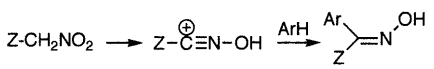


Fig. 38.

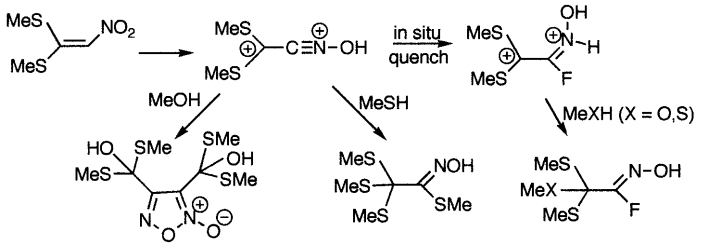


Fig. 39.

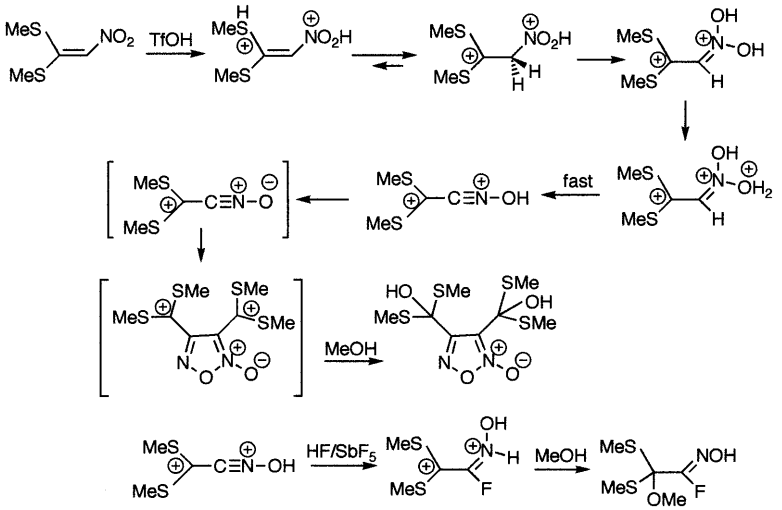


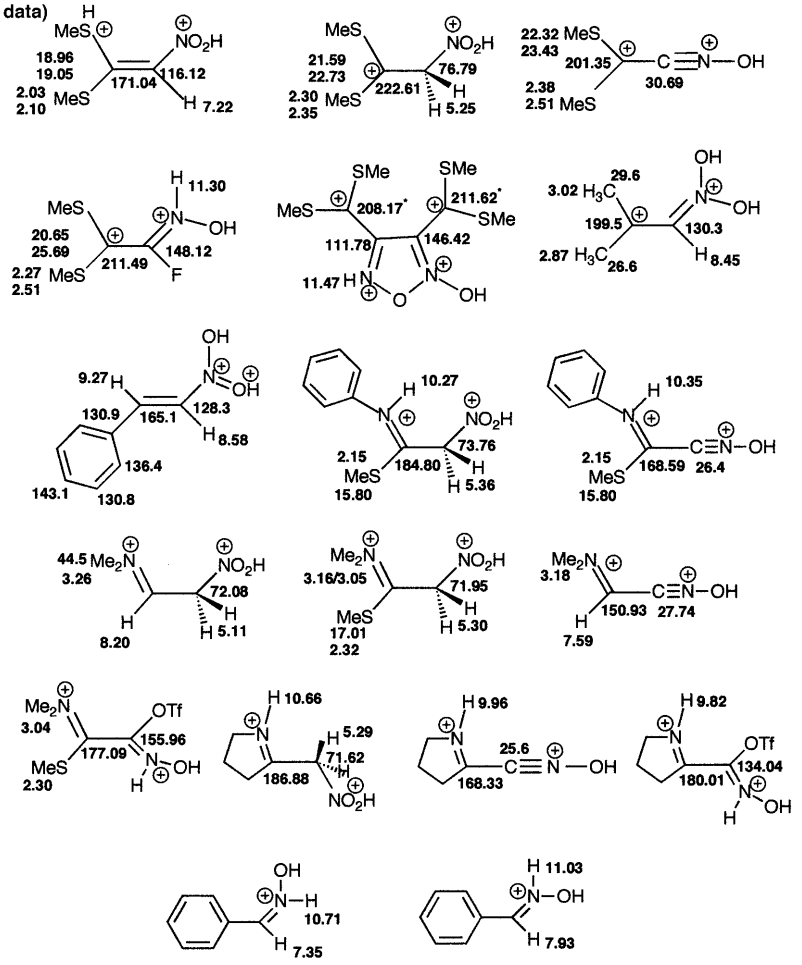
Fig. 40.

In his most recent work, Coustard [45] extended his studies to a series of cyclic and acyclic α-amino derivatives. In TfOH or in $HF{\cdot}SbF_5$ these substrates are first *C,O*-diprotonated to give persistent dications whose stabilities varies as a function of structure. The resulting dications then give hydroxynitrilium ions. In the presence of benzene, hydroxyiminium–ammonium dications were formed. It was again concluded that in the hydroxyiminium group the phenyl ring and the OH are *cis* to each other.

12. NMR data on persistent cations derived form nitroalkene derivatives

For comparative purposes, in this section the NMR data for representative persistent NO_2-diprotonated and *O,C*-diprotonated dications, hydroxynitrilium ions and their related cations including in situ protonated oxime products, which are derived from nitroalkenes in superacid media are gathered in Chart 2.

Chart 2
(multinuclear NMR data)



13. Conclusions

The review has demonstrated that the chemistry of nitro compounds can be greatly extended in superacidic media. An important feature is access to dihydroxyiminium ions by NO_2-diprotonation. In nitro-PAHs steric inhibition to delocalization and nitro buttressing appear to create the driving force for nitro diprotonation. Additional features include nitro cyclization and nitro reduction in superacid media. Nitrosoarenes are *N,O*-diprotonated to give hydroxyiminium–arenium species. They provide the opportunity for comparing $=NHOH^{+2}$ and $=N(OH)_2^{+2}$ linkages and for probing their interplay. Hydroxyiminium–arenium dications have also played an important role in relation to nitrenium ion character. In conjugated nitroalkenes, NO_2 diprotonation leads to dihydroxyiminium–carbenium dications, whereas in nitroalkanes and nitronate salts the protonated *aci* form is a key

intermediate from which hydroxynitrilium cations are formed by further protonation and dehydration. For β-heteroatom-substituted nitroalkenes *C*,*O*-diprotonation is a common feature, followed by formation of hydroxynitrilium ions whose trapping with various nucleophiles has produced a host of open and cyclic oximes.

Nitro group activation in superacid media offers synthetic potentials especially in the heterocyclic chemistry arena and it is expected that this area will continue to develop and mature. Since TfOH is easily handled, it would be logical to expect that superacid nitro activation would enter into contemporary synthetic methods. From a mechanistic perspective, and in relation to biological activity, protonation studies on the nitro derivatives of non-alternant PAHs, such as nitrofluoranthenes which exhibit increased mutagenic/carcinogenic activity, can provide a direct comparison with the alternant nitro-PAH analogs and a means to further test the generality of nitro group diprotonation and cyclization. NMR studies combined with ab initio/IGLO calculations provide the means to examine the charge delocalization mode in the resulting *N*,*N*-dihydroxyiminium–arenium dications.

Acknowledgements

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