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Nitro compounds as the core structures of promising energetic materials and versatile reagents for organic synthesis †

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This review addresses some promising areas of chemistry of nitro compounds extensively developed in recent years in Russia (particularly at the N.D.Zelinsky Institute of Organic Chemistry, Russian Academy of Sciences) and worldwide. The most important results in the synthesis of novel energetic *N*-, *C*- and *O*-nitro compounds are summarized. New environmentally friendly approaches to the preparation of known compounds of this series, used as components of energetic compositions, are considered. Methods for selective transformations of various nitro compounds to valuable products of organic synthesis, primarily biologically active products and their precursors, are systematically analyzed.
The bibliography includes 446 references.

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1. Introduction

Nitro compounds comprise one of the major classes of organic compounds. Their history goes back more than a century and a half. Nitro compounds are generally synthesized by the nitration, which proceeds efficiently with both aliphatic and aromatic hydrocarbons and their certain derivatives in the presence of nitrogen oxides, nitric acid or mixed acids.[1] Industry produces millions of tons of nitro compounds per year. Nitro compounds are widely used as energetic substances (components of explosives, gunpowders, rocket propellants, *etc.*).[2] Besides, nitro compounds are valuable precursors in organic synthesis, because they can be transformed into other compounds used for the synthesis of various practically important materials for civilian applications (polymers, dyes, pharmaceuticals and so on).

In 1953, the Laboratory of Organic Synthesis was set up in the N.D.Zelinsky Institute of Organic Chemistry of the USSR Academy of Sciences (currently ZIOC RAS) for research work in the chemistry of nitro compounds. This laboratory was headed by S.S.Novikov (elected as a Corresponding Member of the Russian Academy of Sciences in 1974), an outstanding scientist in the field of industrial organic chemistry and catalysis. In 1962, S.S.Novikov became the head of the Department of Organic Synthesis, which includes, along with the Laboratory of Organic Synthesis, laboratories headed by Professors A.A.Fainzilberg, L.I.Khmelnitskii and G.A.Shvekhgeimer. This Department has played a great role in the training of researchers and the creation of new scientific schools. For a long time, this research team held a leading position in the Soviet Union and abroad in the field of synthesis of energetic compounds. In 1971, a new Laboratory headed by V.A.Tartakovsky (elected as an Academician in 1992) was founded within the

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framework of this Department. The researchers at this Laboratory have obtained remarkable results. They synthesized dinitramide and its salts comprising a unique class of energy-rich nitrogen – oxygen systems.[3,4] Ammonium dinitramide (ADN) is an oxidant for composite solid rocket propellants (CSRP), which is energetically more efficient than ammonium perchlorate. Besides, ADN has such advantages as environmental soundness of ADN combustion products and their higher transparency due to the absence of chlorine atoms producing hydrogen chloride during combustion. This discovery provided the basis for the development of a new generation of high-impulse density solid rocket propellants in the Soviet Union, and it can be considered as the greatest achievement in the chemistry of energetic substances in the post-Second World War period. These studies were almost two decades ahead the USA and, in US scientists' opinion, were comparable to the Manhattan Project.[5] Apart from dinitramide salts, ZIOC researchers synthesized other types of promising nitro compounds, including aliphatic, aromatic, heterocyclic (in particular polycyclic and cage) structures characterized by extremely high energy properties.[6,7]

Original systematic studies concerning the synthesis of energetic substances could not but address fundamental issues of reactivity and structures of nitro compounds. Traditional areas of application of nitro compounds in organic synthesis include their reduction reactions giving amines or intermediates with retention of the C–N bond,[8–10] the Nef reaction,[11] which leads to the replacement of a C–N bond by a C–O bond, and the generation of α-carbanions in the reaction of primary or secondary aliphatic nitro compounds with bases followed by the involvement of these carbanions as nucleophiles in various reactions.[12,13] The nucleophilic addition to nitroalkenes at the reactive double bond conjugated with the nitro group is also commonly used to form new C–C and C–heteroatom bonds.[14] The discovery of a novel 1,3-dipolar cycloaddition reaction characteristic of the *aci* form of nitro compounds[15,16] was a significant contribution of ZIOC researchers to the chemistry of aliphatic nitro compounds. This reaction allowed the synthesis of various heterocyclic systems, including those of previously unknown types,[17,18] and polyfunctional nitrogen-containing structures used in drug design.[19] Studies performed at the ZIOC RAS have also made a significant contribution to the establishment of other new research areas, which are actively developed in the world, including Russia.

The review addresses modern trends in the chemistry of nitro compounds, with the focus on the areas of research, the foundations of which were laid at the ZIOC RAS. New approaches, including those complying with environmental regulations, to the preparation of promising energetic compounds are summarized and some recently developed efficient methods for selective transformations of nitro compounds into valuable products of organic synthesis are systematically considered. The diversity of methods and substances distinguishes this review from earlier review papers (see the above references), which were devoted to certain aspects of chemistry of nitro compounds with particular chemical structures and for a particular use. Although this review is not exhaustive because of a huge amount of published data, we believe that, due to a broad range of the issues addressed in the review and its analytical character, it will be of interest and useful to a wide range of researchers engaged in organic, industrial and green chemistry.

The following abbreviations are used:
ADN — ammonium dinitramide,
AIBN — azobis(isobutyronitrile),
ANC — aliphatic nitro compound,
bmim — 1-(n-butyl)-3-methylimidazolium,
Bn — benzyl,
Bz — benzoyl,
Cbz — carboxybenzyl,
CL-20 — 2,4,6,8,10,12-hexanitro-2,4,6,8,10,12-hexaazaisowurtzitane (HNIW),
CPME — cyclopentyl methyl ether,
CSRP — composite solid rocket propellant,
Cy — cyclohexyl,
DAF — 3,4-diaminofurazan,
DBU — 1,8-diazabicyclo[5.4.0]undec-7-ene,
Dpm — diphenylmethyl,
dr — diastereomeric ratio,
EC — explosive composition,
ee — enantiomeric excess,
EG — ethylene glycol,
EM — energetic material,
ES — explosive substance,
FG — functional group,
GABA — gamma-aminobutyric acid,
hmim — 1-(n-hexyl)-3-methylimidazolium,
HMPTA — hexamethylphosphoric triamide,
HMX — 1,3,5,7-tetranitro-1,3,5,7-tetraazacyclooctane,
HWE — Horner – Wadsworth – Emmons reaction,
IL — ionic liquid,
KHMDS — potassium hexamethyldisilazide,
LA — Lewis acid,
LB — Lewis base,
LHMDS — lithium hexamethyldisilazide,
m-CPBA — *meta*-chloroperoxybenzoic acid,
1-mim — 1-methylimidazolium,
MPa — megapascal,
Ms — mesyl,
MW — microwave treatment,
NA — nitronic acid,
NACs — nitro-*NNO*-azoxy compounds,
NAP — *N*-aminopyrazole,

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Translation: T.N.Safonova

NC — nitrocellulose,
NMO — *N*-methylmorpholine *N*-oxide,
PEG — polyethylene glycol,
Pic — picryl,
PMB — *para*-methoxybenzyl,
pmim — 1-propyl-3-methylimidazolium,
PMP — *para*-methoxyphenyl,
Py — pyridyl,
RDX — 1,3,5-trinitro-1,3,5-triazacyclohexane,
rr — regioisomeric ratio,
rt — room temperature,
sc — supercritical,
TAT — 2,4,6-triaminotoluene,
TATB — 1,3,5-triamino-2,4,6-trinitrobenzene,
TBS — *tert*-butyldimethylsilyl,
TC — three-component mixture,
Tebsa — *N*-(4-sulfonic acid) butyl triethylammonium,
Tf — triflate,
TFA — trifluoroacetic acid,
TFE — 1,1,1,2-tetrafluoroethane,
TIPS — triisopropylsilyl,
TMS — trimethylsilyl,
TNB — 1,3,5-trinitrobenzene,
TNT — 2,4,6-trinitrotoluene,
Tr — trityl.

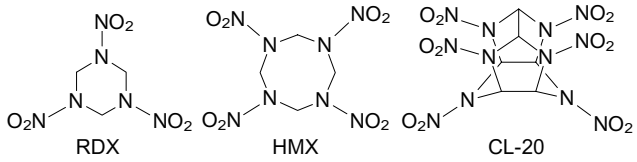
2. New methods for the synthesis of promising energetic compounds

Nitro compounds (in particular, polynitro compounds) are core structures of most of energetic materials (EMs) for military and civilian applications. Many of these compounds can release a significant amount of stored chemical energy upon external stimulation (shock, friction, heat, spark and so on) through a fast redox reaction accompanied by combustion or detonation. Due to this property, nitro compounds are commonly used in CSRPs, various pyrotechnic compositions and explosive compositions (ECs). The nitro group in nitro compounds can be bound to nitrogen (*N*-nitro compounds), carbon (*C*-nitro compounds) and oxygen (nitro esters) atoms. This Chapter addresses selected methods for the synthesis of promising energetic *N*- and *C*-nitro compounds developed in recent years and green approaches to the preparation of different types of energetic nitro compounds that have recently gained popularity due to reduction of negative environmental impacts.

2.1. Energetic *N*-nitro compounds

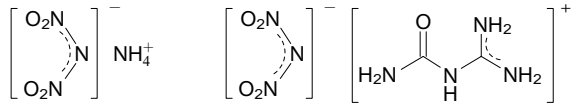
The high-enthalpy nitramine group ($N-NO_2$) containing active oxygen is one of the most efficient explosophores. This group is present in most of basic components of commercially important energetic compositions, including powerful ECs, gunpowders and CSRPs. 1,3,5-Trinitro-1,3,5-triazacyclohexane (RDX) and 1,3,5,7-tetranitro-1,3,5,7-tetraazacyclooctane (HMX) are the most important components (structures RDX, HMX, CL-20). 1,3,5-Trinitro-1,3,5-triazacyclohexane is characterized by high brisance with the detonation velocity (V_D) $\approx$ 8440 m s^{-1} and the density (d) = 1.70 g cm^{-3}. This compound is stable and is widely used in different weapon systems as press powders with other explosive substances (ESs) or in combination with a polymer binder and a plasticizer.[20] 1,3,5,7-Tetranitro-1,3,5,7-tetraazacyclooctane is an even more powerful ES ($V_D \approx 9110$ m s^{-1}) due to its high density (d = 1.90 g cm^{-3}). The use of HMX in special compositions is limited by its relatively high cost.[21] 2,4,6,8,10,12-Hexanitro-2,4,6,8,10,12-hexaazaisowurtzitane (CL-20) is the most powerful explosive[22,23] in the series of nitramine-containing compounds. Due to the cage skeleton of isowurtzitane, CL-20 has a very high density (d = 2.04 g cm^{-3}) and detonation velocity ($V_D \approx 9380$ m s^{-1}). Hence, the latter compound can be considered as a basic component of new weapon systems.

Structures RDX, HMX, CL-20



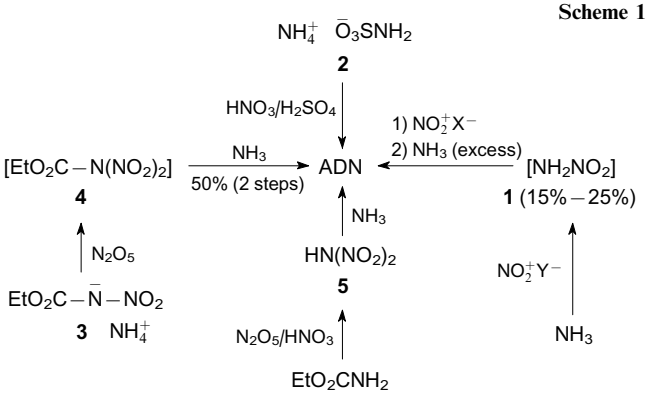
In the past decades, the synthesis and properties of nitramine-containing ionic compounds have attracted great attention. The dinitramide anion was synthesized for the first time by Tartakovsky and co-workers in 1971. This was among the most significant achievements in the chemistry of EMs and had served as the basis for the development of a new generation of CSRPs for missile complexes with different basing systems. From the very beginning, these studies were classified and not available to the public. Some of these results were published as late as 1994 – 1995.[24–30] Nevertheless, the priority of Russian researchers is widely recognized and is beyond doubt.[5] Dinitramide salts containing different inorganic and organic cations were synthesized. Ammonium dinitramide (structures ADN and FOX-12) is of particular interest. This compound, being superior in energy to ammonium perchlorate, is environmentally benign because propellant combustion products are free from toxic chlorine-containing compounds. Besides, due to a high active oxygen content in ADN, such strong reducing agents as aluminium or boron can be introduced into propellants, thereby increasing their specific impulse. It was suggested to use carbamoylguanidinium salt (FOX-12) as a low-sensitivity explosive in CSRPs and ordinary weapons.[31]

Structures ADN, FOX-12



Unique properties of ADN have stimulated researchers to develop facile and efficient methods for the synthesis of this compound on a large scale. An attractive method for the synthesis of ADN is based on the nitration of excess ammonia with dinitrogen pentoxide or nitronium salts proceeding through the formation of nitramide **1** (Scheme 1). However, the yield of the target product was not higher than 25% even under thoroughly optimized conditions.[32] The nitration of sulfamic acid ammonium salt (**2**) with an excess of a mixture of nitric and sulfuric acids (1 : 2) resulted in a higher yield ($\sim$45%) of ADN.[33] The drawback of this method is a considerable energy expenditure required to maintain a low temperature of the reaction (from -35 to -45 °C). A convenient two-step

Scheme 1

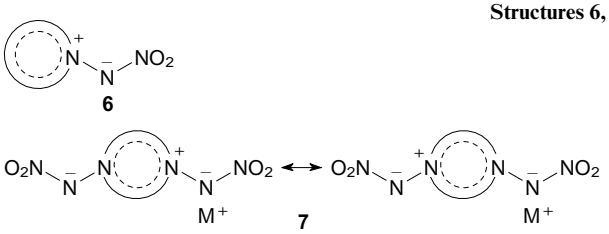


X = NO_3; Y = BF_4, HS_2O_7; ADN is ammonium dinitramide

method for the synthesis of ADN involves the reaction of ammonium salt of nitrourethane (**3**) with dinitrogen pentoxide and the ammonolysis of the resulting dinitrourethane (**4**). Meanwhile, US researchers believe that the most efficient approach to prepare ADN is based on the nitration of the available substrate, ethyl carbamate, with fuming nitric acid (N_2O_5 – HNO_3) followed by neutralization of the resulting dinitraminic acid (**5**) with ammonia.[34] This reaction occurs at moderately low temperatures (−20 °C) and can serve as the basis for the development of industrial production of ADN.

N-Nitroimides comprise another promising type of energetic salt structures. In heterocyclic *N*-nitroimides **6**, the negatively charged nitramine moiety is directly bound to the positively charged nitrogen atom of the heterocycle (structures **6**, **7**). Katritzky and co-workers[35, 36] were the first to prepare these compounds based on pyridinium. More recently, nitroimides of the 1,2,4-triazole, benzo-1,2,3-triazole and benzimidazole series were synthesized.[37] Bis(*N*-nitroimido)azole salts **7**, in which the positive charge is delocalized over two N atoms of the heterocycle, while the negative charges are located on two *N*-nitramine groups, are of particular interest.

Structures 6, 7



First compounds of this type, potassium salts of 1,3-bis(*N*-nitroimido)-1,2,3-triazole **8a** and 1,3-bis(*N*-nitroimido)benzo-1,2,3-triazole **9a**, were synthesized by Shitov *et al.*[38] (Scheme 2). The amination of 1-aminotriazoles **10** and **11** with *O*-picrylhydroxylamine (picryl is 2,4,6-trinitrophenyl) followed by the treatment with nitric acid afforded 1,3-diaminotriazolium nitrates **12** and **13**, respectively. The nitration of the latter with nitronium tetrafluoroborate in acetonitrile and the neutralization of the products with potassium acetate gave salts **8a** and **9a** in good yields.

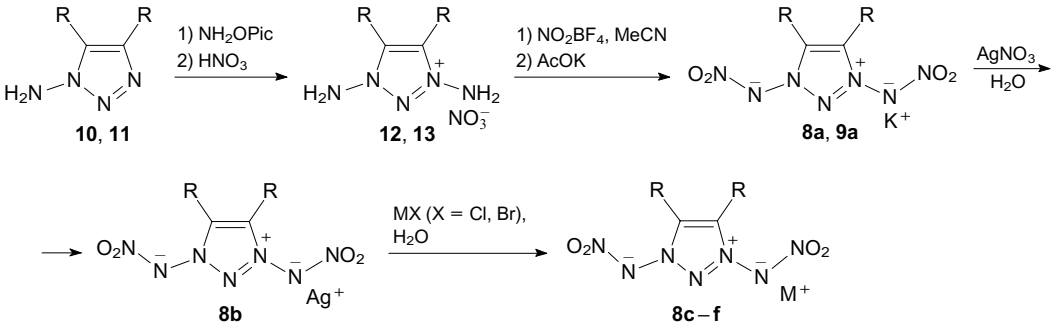
Klapötke *et al.*[39] synthesized a series of 1,3-bis(*N*-nitroimido)-1,2,3-triazole salts **8b**–**f** (Scheme 2). The reaction of potassium salt **8a** with silver nitrate in water produced silver salt **8b** in 58% yield. Exchange reactions of salt **8b** with ammonium chloride, hydroxylammonium chloride, hydrazinium bromide and triaminoguanidinium chloride gave the corresponding salts **8c**–f in 69% – 99% yields. The structures of the salts were confirmed by X-ray diffraction. Differential scanning calorimetry analysis showed that salts **8a**–**f** are thermally stable compounds with decomposition onset temperatures (T_{dec}) of 149 – 238 °C.

The synthetic scheme for the preparation of salt **8a** was successfully applied to prepare potassium salts of 1,3-bis(*N*-nitroimido)imidazole **14** and 1,4-bis(*N*-nitroimido)-1,2,4-triazole **15a** (Scheme 3).[40] The amination of 1-aminoimidazole **16** and 4-amino-1,2,4-triazole **17a** gave the corresponding diamino derivatives **18** and **19**. Their nitration with nitronium tetrafluoroborate followed by the treatment with a base resulted in the formation of salts **14** and **15a** in ~50% yield. An alternative route enabled the synthesis of salt **15a** and 3,5-disubstituted salts **15b**,**c**.[41, 42] The nitration of 4-aminotriazoles **17a**–**c** with ethyl nitrate in the presence of a base affords 4-*N*-nitroimides **20a**–**c**, which can easily be transformed into compounds **21a**–**c** and then into 1,4-bis(*N*-nitroimido)-1,2,4-triazoles **15a**–**c**. Salts **14** and **15a**–**c** melt above 150 °C and feature good thermal stability.

Another representative of bis(*N*-nitroimido)azole salts, potassium salt of 2,7-bis(nitroimido)-7*H*-[1,2,4]triazolo[4,3-*b*][1,2,4]triazole **22**, was synthesized from 7*H*-[1,2,4]triazolo[4,3-*b*][1,2,4]triazole-7-amine **23** by the sequential amination and nitration of diamine **24** (Scheme 4).[40] The yield of stable salt **22** (the melting point is 163 – 167 °C) was 70%.

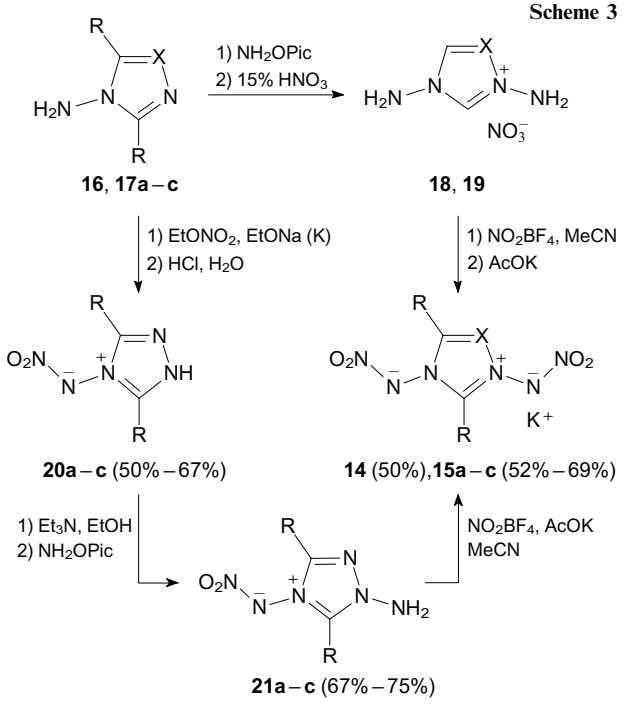
An important achievement was the development of methods for the synthesis of a new class of *N*-nitro compounds promising in terms of energy. In these compounds, the nitro group is directly bound to the distal nitrogen atom

Scheme 2



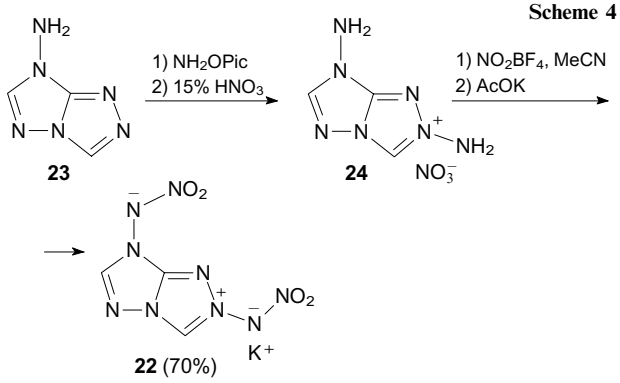
8: R = H, M = K (**a**, 73% yield), Ag (**b**, 58%), NH_4 (**c**, 71%), NH_3OH (**d**, 69%), N_2H_5 (**e**, 99%), $C(NHNH_2)_3$ (**f**, 95%);
9a: R – R = C_4H_4 (benzene ring moiety), M = K (80%); **10**, **12**: R = H; **11**, **13**: R – R = C_4H_4 (benzene ring moiety); Pic is picryl

Scheme 3



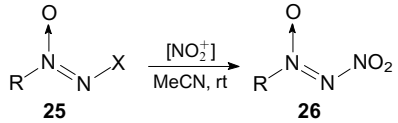
14, **16**, **18**: X = CH; **15**, **17**, **19**: X = N, R = H (**a**), Me (**b**), Ph (**c**)

Scheme 4



of the energetic diazene oxide moiety. The first nitro-*NNO*-azoxy compounds (NACs) were synthesized by Churakov and co-workers in 1984. However, the spectroscopic characteristics (IR and Raman spectra) of these compounds were published as late as 1994;[43,44] the methods for their synthesis were reported in 1996 [45] and 1997.[46] This class of compounds continues to attract considerable attention from researches.[47,48] Azoxy compounds **25** containing such substituents as Bu^t, $C(O)CH_3$, CO_2Bu^t or $C(O)NH_2$ at the distal N atom serve as the starting reagents for the synthesis of NACs. The reactions of these compounds with nitronium salts (NO_2BF_4, $(NO_2)_2SiF_6$) or dinitrogen pentoxide afford target products **26** in good yields (75% – 91%) (Scheme 5).

Scheme 5

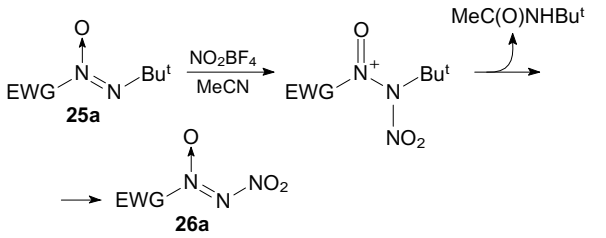


X = Bu^t, $C(O)CH_3$, CO_2Bu^t, $C(O)NH_2$; R is alkyl, aryl, hetaryl;
$[NO_2^+]$ = NO_2BF_4, $(NO_2)_2SiF_6$, N_2O_5

According to the X-ray diffraction data, the nitro group in the resulting NACs is in *trans* position to the substituent R and the angle between its plane and the plane of the azoxy moiety is about 90°.[45,48]

A convenient method for the synthesis of compounds **26a** bearing electron-withdrawing heterocyclic substituents is based on the nitration of azoxy compounds **25a** with nitronium tetrafluoroborate. The nitration is generally performed in acetonitrile at room temperature. The reaction time varies from several hours to several days depending on the structure of the starting compound. The *tert*-butyl cation that is released in the course of the reaction interacts with acetonitrile and, after the treatment of the reaction mixture with water, gives *N*-*tert*-butylacetamide (Scheme 6).

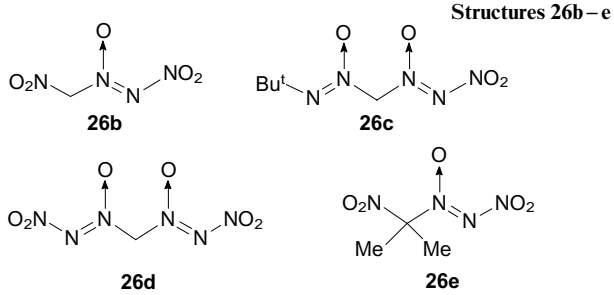
Scheme 6



EWG = R = methylfurazanyl, 1-methyl-3-nitro-1H-1,2,4-triazol-5-yl

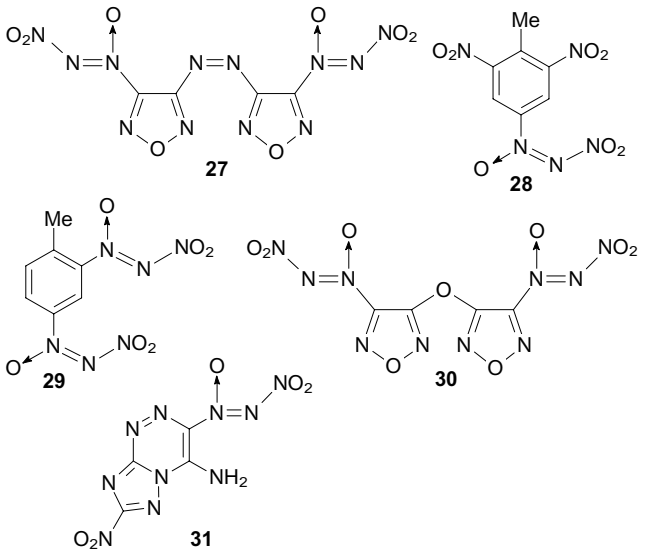
Thermal stability of aliphatic NACs depends on the mobility of the proton at the α-carbon atom. Thus, products **26b**,**d** are the least stable among compounds **26b** – **e**; they decompose at room temperature (structures **26b** – **e**). Compound **26c** is more stable (T_{dec} = 88 °C, DSC data). Product **26e**, which does not contain a proton at the α position to the diazene oxide group, proved to be the most stable aliphatic NAC (T_{dec} = 104 °C).

Structures 26b – e



Nitro-*NNO*-azoxy compounds based on electron-withdrawing arenes and heterocycles (structures **27** – **31**) are even more stable. Thus, the decomposition temperature of furazan derivative **27** is 132 °C.[49] Nitro-*NNO*-azoxy compounds **28** and **29** containing electron-withdrawing aromatic groups have similar parameters. Difurazanyl ether **30** melts at 66 °C.[50] Although the decomposition temperature of **30** was not reported, it would be expected that it is not higher than that of aza analogue **27**. The recently synthesized polynitrogen compound **31** (T_{dec} = 154 °C, DSC data) [48] is the most thermally stable of all the characterized NACs. The stability of the structure is apparently attributed to the fact that the thermal decomposition occurs in the solid rather than the liquid state. Hence, high-melting

Structures 27 – 31

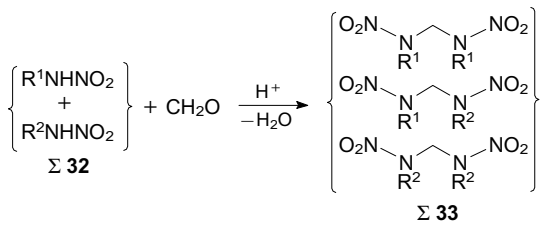


point compounds of the heterocyclic series hold promise as candidates for the development of new energetic NACs suitable, taking into account their properties, for the practical application as components of energetic materials.

At the present time, the possibility to increase the efficiency of energetic materials using the available component basis is almost exhausted. Further progress in energy supply of new systems requires more efficient basic components or, alternatively, modification or optimal combinations of the available components. The synthesis of fundamentally new components is evidently the mainstreaming strategy in this research area. However, the way from the synthesis of a potential component to its practical applications in real compositions is extremely complex and long-lasting. Apart from high requirements to the energy and operational characteristics of compounds, the availability of the sources, the manufacturability and safety of the products and some other, often mutually exclusive, requirements should be taken into account. Hence, US researchers consider the large-scale programme on development of ADN for missile applications, which was accomplished in the Soviet Union within seven years, as an example of the extremely fast introduction of energetic materials into practice.

In some cases, the optimal combination of known types of complementary energetic compounds, which impart required properties to EMs, can give good results. Spitzer *et al.*[51] studied the crystal structures and plasticizing ability of a series of *N*,*N*′-dialkylmethylene bisnitramines **33** and proposed their mixtures (**Σ 33**) as energetic plasticizers of propellants, which can be used in a wide temperature range.

Scheme 7

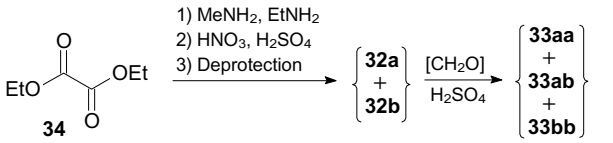


R^1, R^2 = Me (**a**), C_2H_5 (**b**), n-C_3H_7 (**c**), i-C_3H_7 (**d**)

Linear methylene bisnitramines **33** are usually synthesized by the condensation of primary nitramines **32** with formaldehyde in an acidic medium.[52] Composite products **Σ 33** were synthesized by a similar procedure using the simultaneous condensation of primary nitramines **Σ 32** with formaldehyde (Scheme 7).

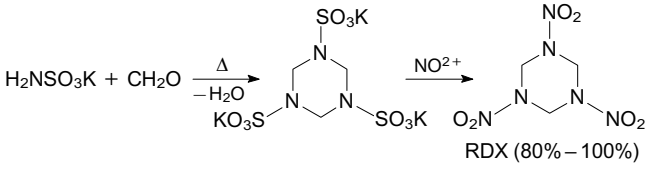
Vijayalakshmi *et al.*[53] also reported high plasticizing ability of *N*,*N*′-dialkylmethylene bisnitramines and, particularly, their mixtures in a wide temperature range. Available diethyl oxalate (**34**) was used as the only starting compound to prepare an effective mixed plasticizer. Compound **34** was transformed into primary nitramines **32a**,**b** by amidation, nitration and aminolysis (Scheme 8). The subsequent condensation of the components of the mixture (compounds **32a**,**b**) with formaldehyde gave a three-component plasticizer containing lower dialkylmethylene bisnitramines **33aa**, **33ab**, **33bb**. However, the industrial application of this method is limited by the multistep synthetic procedure and rather severe conditions required for the nitration of precursors generated from compound **34**.

Scheme 8



Sulfamic acid derivatives hold more promise as the starting reagents. Sulfamic acid salts have been used in the synthesis of nitramines for many years. For instance, Stickland and Ross[54] suggested that these derivatives can be utilized in the industrial production of RDX (known as the W-method) (Scheme 9). The chemical aspect of this simple and efficient two-step reaction was considered in detail by Binnie *et al.*[55]

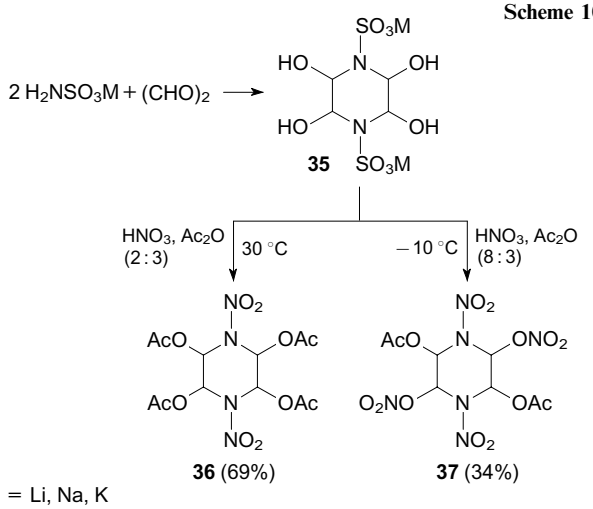
Scheme 9



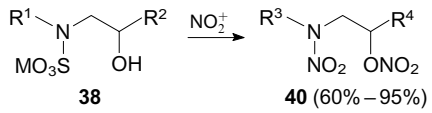
Another method for the synthesis of nitramines based on the condensation of sulfamates with glyoxal was discovered by Dinwoodie *et al.*[56] The reaction affords 2,3,5,6-tetrahydropiperazine-1,4-disulfonic acid salt **35**, and its treatment with the $HNO_3 - Ac_2O$ nitrating mixture gives *N*,*N*′-dinitropiperazine derivatives **36** or **37** depending on the composition of the nitrating system (Scheme 10).

Advantages of the synthetic approach to polynitramines based on sulfamates as components is the availability of the starting compounds, the possibility of using both strong ($HNO_3 - H_2SO_4$) and mild ($HNO_3 - AcOH$) nitrating systems for the nitration of sulfamates and the retention of activity of the mixed acid during nitration (sulfuric acid as a by-product). Besides, alkylsulfamates can be readily involved in the Mannich condensation and react with oxiranes. This allows the preparation of substrates for the synthesis of a wide range of functionalized nitramines with a

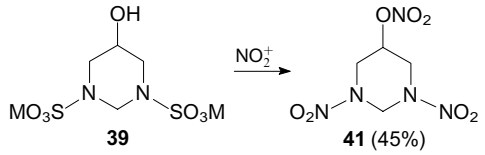
Scheme 10



Scheme 11



M = K, Na, NH_4; R^1, R^3 = Alkyl, $(CH_2)_nOX$; R^2, R^4 = H, Alkyl, CH_2OX, CH_2Cl (X = H, NO_2)

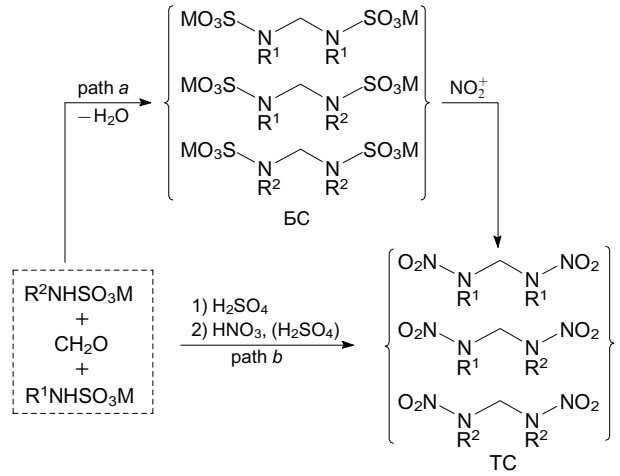


specified set of properties. In particular, substituted β-hydroxyalkyl-*N*-sulfamates **38** and **39** were used to synthesize β-nitoxyalkyl-*N*-nitramines **40** and **41**, respectively, in good yields (Scheme 11).[57, 58]

The sulfamate method proved to be particularly useful for the preparation of mixed nitramine plasticizers of gunpowder and CSRPs, which are characterized by the optimal combination of high energy-mass properties, low melting points (glass transition temperatures), good plasticizing ability, low sensitivity to mechanical stimuli, good compatibility with other components of EMs and so on. The synthesis of a mixed plasticizer includes the simultaneous homo- and cross-condensation of two sulfamic acids followed by the nitration of its products.

This very simple, cost-effective and convenient procedure is applied to assemble three-component (TC) *N*,*N*′-dialkylmethylene bisnitramine mixtures with required composition and structure (Scheme 12). The process can be accomplished in two ways. One approach (path *a*) involves the condensation in neutral or weakly acidic conditions (pH 5.0 – 7.0) using water distillation followed by the nitration of the resulting mixture of bis-suflamates (BSs) with a sulfuric – nitric acid mixture.[59] In another method (path *b*), the condensation of sulfamates is performed in 87% H_2SO_4 as a water consuming agent and the resulting three-component mixture is treated without isolation with concentrated HNO_3 or a sulfuric – nitric acid mixture.[60] The method is suitable for the preparation of active-oxygen rich TCs containing nitramine and nitrate groups (R^1, R^2 = $(CH_2)_nONO_2$). An alternative method for the synthesis of this type of mixed plasticizers is based on the condensation of sulfamic acid salts with ethylene oxide and the subsequent nitration of the resulting *N*-(hydroxyethyl)-sulfamates.[57] Nitrate groups in the reaction products can easily be replaced by high-enthalpy azide groups on treatment with sodium azide, which significantly extends the range of energetic structures accessible by this method.[61, 62]

Scheme 12



R^1, R^2 = alkyl, $(CH_2)_nONO_2$; M = H, K, Na, NH_4

2.2. Energetic *C*-nitro compounds

C-Nitro compounds (polynitro compounds) are also involved in numerous EMs. For instance, 2,4,6-trinitrotoluene (TNT) is the most important shattering explosive, which is commercially produced on an enormous scale and is widely used in military loads (in particular, in combination with RDX and HMX). This compound is thermally and chemically stable and is virtually insensitive to shock and friction. However, its detonation velocity (6940 m s^{-1} at a density of 1.64 g cm^{-3}) is much lower than that of RDX, HMX and CL-20. According to thermodynamic calculations, nitro derivatives of nitrogen- and nitrogen – oxygen-containing heterocycles should have superior energy properties. These compounds are characterized by a much higher enthalpy of formation compared to the benzene ring and contain a smaller number of 'ballast' carbon atoms. Among these compounds, *C*-nitro derivatives of 1,2,5-oxadiazole (furazan), 1,2,5-oxadiazole 2-oxide (furoxan), pyrazole, 1,2,3-triazole, 1,2,4-triazole and tetrazole series have attracted great attention. Methods for the synthesis and properties of nitro derivatives of 1,2,3-triazole, 1,2,4-triazole and tetrazole are summarized in earlier reviews.[63, 64] In this review, we systematically consider recent data on energy-rich furazan, furoxan and pyrazole derivatives containing several nitro groups and/or other explosophores.

2.2.1. Nitrofurazans and nitrofuroxans

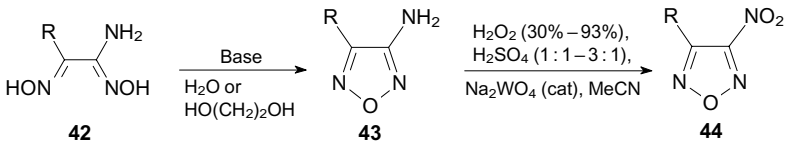
The furazan and furoxan rings have high enthalpy of formation, are rather stable and contain an active oxygen atom (atoms). Therefore, they hold promise as the core structures for EMs.[65 – 67] Moreover, the introduction of a nitro group at carbon atoms of the furazan and furoxan rings improves the oxygen balance and leads to an increase in the density and detonation parameters of the resulting derivatives.[68] The synthesized compounds include both monocyclic structures containing, apart from nitro groups,

other explosophores (*e.g.*, nitrate, azide or nitramine groups) and polycyclic derivatives, in which heterocycles are linked to each other either directly or by different bridges [O, N═N, N(O)═N]. Many compounds of this type belong to energetic materials.[69]

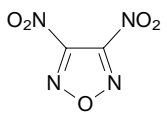
The commonly used method for the synthesis of nitrofurazans is based on the oxidation of aminofurazans with peroxide oxidants in an acidic medium. In many cases, available 3,4-diaminofurazan (DAF) serves as the starting compound. Aminofurazans containing electron-donating substituents are rather easily oxidized, for example, with trifluoroperacetic acid. However, attempts to synthesize nitrofurazans with electron-withdrawing substituents have long been unsuccessful. The desired result was achieved using mixtures of aqueous hydrogen peroxide with different concentrations and sulfuric acid as the oxidant and sodium tungstate or ammonium persulfate as the catalyst.[70, 71] These methods enabled the synthesis of energetic nitrofurazans **44** from aminofurazans **43**, which were prepared from aminoglyoximes **42** (Scheme 13). In particular, this approach was applied to prepare dinitrofurazan (**44a**),[70, 71] 3-cyano-4-nitrofurazan (**44b**),[70] 5-(3-nitrofurazan-4-yl)-1*H*-[1,2,4]triazolo[4,5-*c*]furazan (**44c**),[72] 4,4-dinitrobifurazan (**44d**),[73] 4,4-dinitrodifurazanyl ether (**44e**),[74] 4,4-dinitroazofurazan (**44f**)[75] and 4,4-dinitroazoxyfurazan (**44g**).[76, 77] Some physicochemical parameters of these compounds were experimentally determined and their energy characteristics were calculated.[69, 71, 72]

The further development of this approach resulted in the preparation of polynuclear nitrofurazans **45** – **49** containing up to four furazan rings bridged by an oxygen atom or azo(azoxy) groups.[78] The calculated specific impulse of metal-free composite solid propellants including compounds **45** – **49** as components is 2 – 4 s higher than the corresponding parameter of propellants containing aluminium hydride. Similar conditions (90% H_2O_2 –

Scheme 13

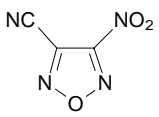


42 **43** **44**



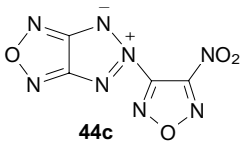
44a

ΔH_f° = 230.1 kJ mol^{-1}
d = 1.62 g cm^{-3} (liq),
T_{dec} = 220 °C



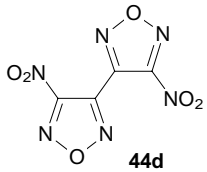
44b

ΔH_f° = 350.6 kJ mol^{-1},
d = 1.49 g cm^{-3} (liq),
T_{dec} = 200 °C



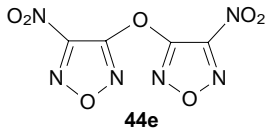
44c

ΔH_f° = 841.0 kJ mol^{-1},
d = 1.92 g cm^{-3}



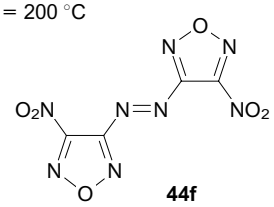
44d

ΔH_f° = 422.6 kJ mol^{-1},
d = 1.85 g cm^{-3}



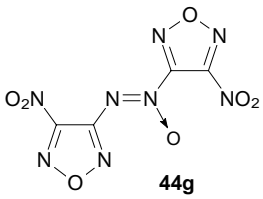
44e

ΔH_f° = 305.4 kJ mol^{-1},
d = 1.907 g cm^{-3}



44f

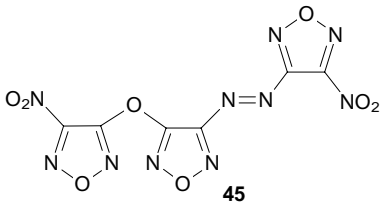
ΔH_f° = 702.9 kJ·mol^{-1},
d = 1.73 g cm^{-3},
T_{dec} = 180 °C



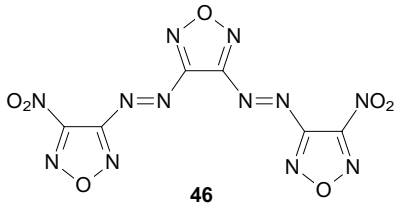
44g

ΔH_f° = 647.2 kJ mol^{-1},
d = 1.81 g cm^{-3}

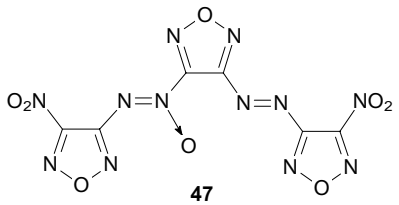
Structures 45 – 50



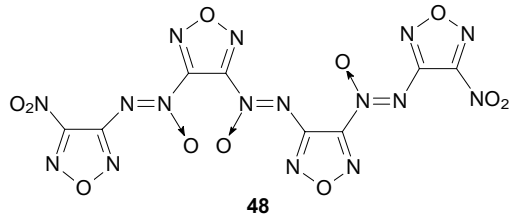
45



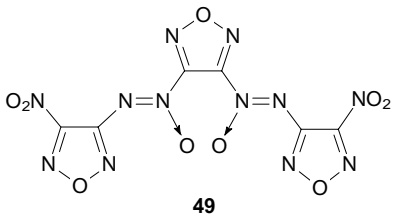
46



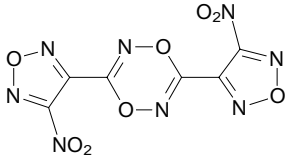
47



48

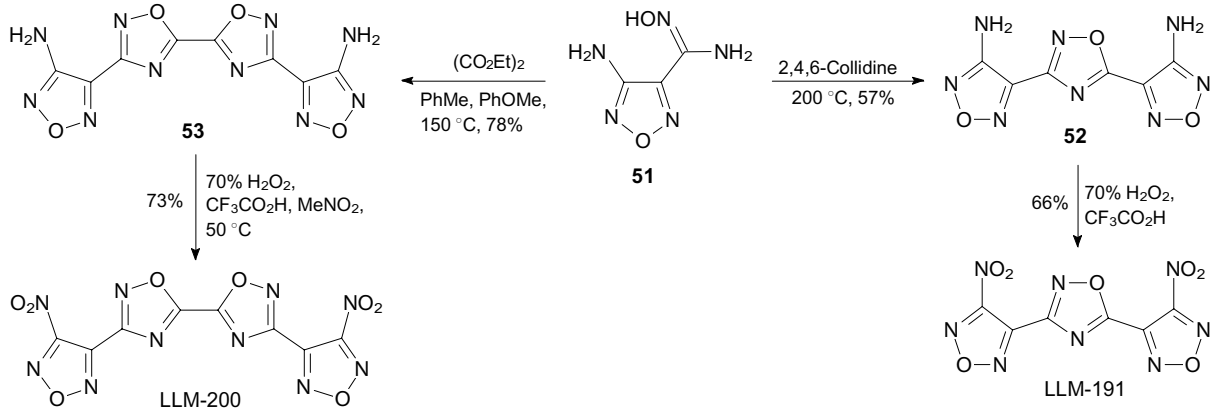


49



50

Scheme 14

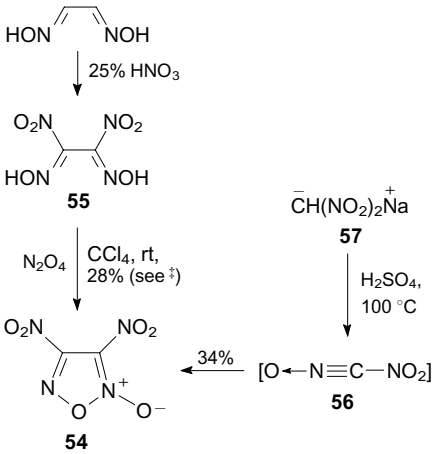


$Na_2WO_4-H_2SO_4$) have recently been used to prepare 3,6-bis(nitrofurazanyl)-1,4,2,5-dioxadiazine **50** by oxidation of appropriate diamine.[79]

Oxadiazole-bridged aminofurazans are synthesized from appropriate amidoximes. For instance, the pyrolysis of aminofurazanyl amidoxime **51** at 200 °C in collidine gave compound **52**. Tetracyclic compound **53** was synthesized by heating amidoxime **51** with diethyl oxalate at 150 °C in a mixture of toluene and anisole. The subsequent oxidation of diamines **52** and **53** with the 70% H_2O_2 – trilfuoroacetic acid (TFA) system afforded polynuclear nitrofurazans LLM-191 and LLM-200 with a rather high density (1.91 and 1.94 g cm^{-3}, respectively) (Scheme 14).[80]

Nitrofuroxans can be synthesized by either oxidation of aminofuroxans or by methods specific for furoxan derivatives, which include the oxidative cyclization of nitroglyoximes, dehydration of α-nitrooximes, synthesis from unsaturated compounds and cascade transformations of the dinitromethane anion. Since diaminofuroxan is currently unavailable,[81] dinitrofuroxan **54** was synthesized by the oxidation of dinitroglyoxime **55**,[82] which was generated by the nitration of glyoxime with dilute nitric acid, or by the cyclodimerization of unstable nitro formonitrile oxide **56**,[83] produced by the dehydration of dinitromethane sodium salt **57** with concentrated H_2SO_4 (Scheme 15). Dinitrofuroxan **54** contains an excess of active oxygen and is a strong oxidizing agent; however, low stability interferes with its use in EMs.

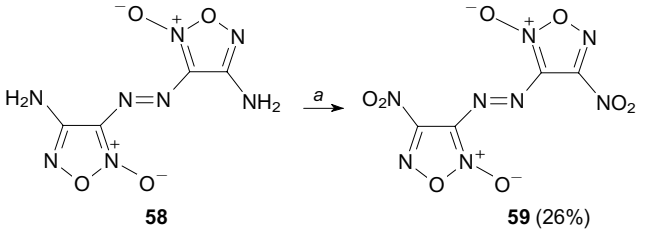
Scheme 15



‡ The refined experimental data published by Godovikova *et al.*[82]

3-Aminofuroxans are not transformed into 3-nitrofuroxans in the presence of oxidizing agents, but isomeric 4-aminofuroxans containing no strong electron-withdrawing substituents can be oxidized by trifluoroperacetic acid.[7] Substrates bearing electron-withdrawing groups are oxidized under the same conditions as those used for the oxidation of aminofurazans. For instance, 4,4′-diamino-3,3′-diazenofuroxan **58** gives, although in low yield, 4,4′-dinitro-3,3′-diazenofuroxan **59** when treated with the 85% H_2O_2/Na_2WO_4/96% H_2SO_4 oxidizing system (Scheme 16).[84] In a subsequent study, the yield of product **59** was increased to 69% by employing trifluoromethanesulfonic acid instead of H_2SO_4.[85] Compound **59** is currently one of the most powerful ESs [$V_D \approx 10\,000$ m s^{-1}, $d = 2.002$ g cm^{-3} (Ref. 84) $d = 1.981$ g cm^{-3} (Ref. 85)].

Scheme 16



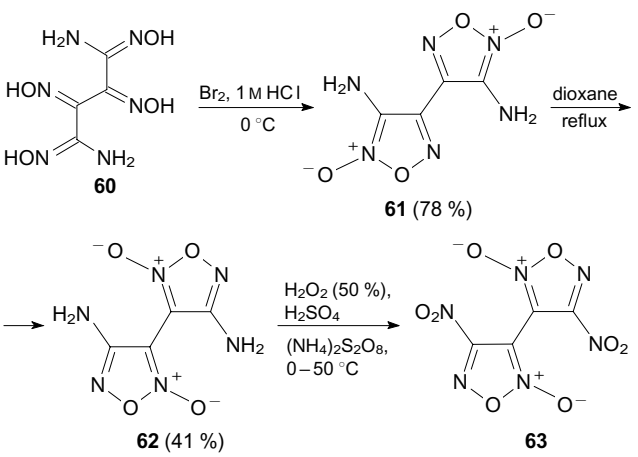
(*a*) H_2O_2 (85%), Na_2WO_4, 96% H_2SO_4, 30 °C

The oxidation of 4,4′-diamino-3,3′-bifuroxan **62** with 50% H_2O_2 in concentrated H_2SO_4 in the presence of $(NH_4)_2S_2O_8$ as the catalyst afforded target 4,4′-dinitro-3,3′-bifuroxan **63** in trace amounts.[86] Starting diamine **62** was prepared by thermal isomerization of 3,3′-diamino-4,4′-bifuroxan **61**, the oxidation product of tetraoxime **60**, with bromine in hydrochloric acid (Scheme 17).

The oxidation gave energetic 3,4-bis(4-nitrofuroxan-3-yl)furoxan **66** ($V_D = 9500$ m s^{-1}, $d = 1.91$ g cm^{-3}). In this case, to transform diamine **65** into target product **66** a complex of hypochloric acid with acetonitrile was required. The initial diamine **65** was synthesized from 4-amino-3-hydroxyiminoylfuroxan **64** by a multistep procedure (Scheme 18).[87]

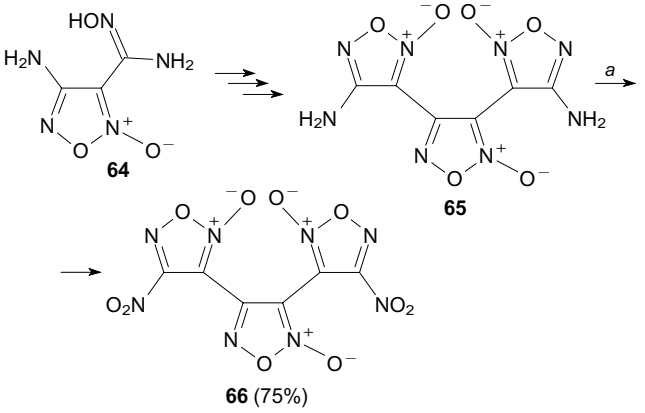
The reaction of a series of unsaturated compounds with nitrosating agents also affords nitrofuroxans. Thus, 1-R-acrylic acids (**67**, R = Alk, Ar) are regioselectively transformed into 4-nitrofuroxans **69** by the treatment with excess $NaNO_2$ in AcOH. Apparently, the furoxan ring formation

Scheme 17



60 **61** (78 %) **62** (41 %) **63**

Scheme 18

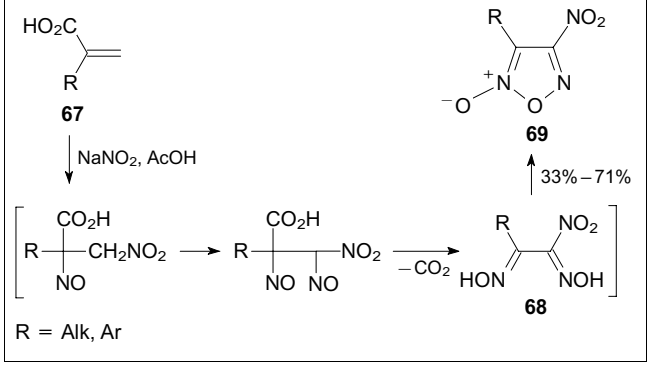


64 **65** **66** (75%)

(*a*) HOF·MeCN, MeCN, 0 °C

occurs through intermediate nitroglyoximes **68**, which undergo spontaneous oxidative cyclization under the reaction conditions (Scheme 19).[88] 3-Aryl-4-nitrofuroxans (**69**, R = Ar) are produced by a similar reaction of styrene and its derivatives with the nitrosating agents $NOBF_4$ (Ref. 89) or $NaNO_2 - H^+$.[90]

Scheme 19

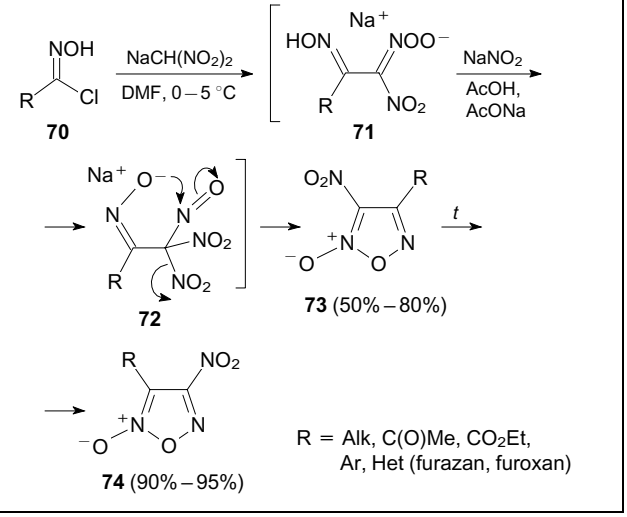


67 **69** **68**

R = Alk, Ar

The general method for the synthesis of nitrofuroxans, allowing the preparation of both positional isomers of these compounds with different substituents, is based on a tandem one-pot reaction. In the first step, dinitromethane salt is acylated with appropriate hydroxamic acid chlorides **70**. The subsequent nitrosation of acylation product **71** is accompanied by cyclization of intermediate **72** to 3-nitrofuroxans **73** (Scheme 20). Products **73** are rearranged on heating into thermodynamically more favourable 4-nitro isomers **74**. This considerably extends the scope of the method.[91,92] The possibility of preparing starting compounds **70** immediately before the reaction from appropriate oximes and *N*-chlorosuccinimide makes this method even more attractive.[93]

Scheme 20

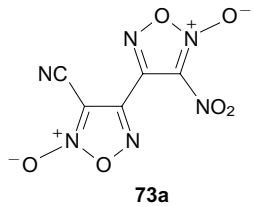


70 **71** **72** **73** (50% – 80%) **74** (90% – 95%)

R = Alk, C(O)Me, CO_2Et, Ar, Het (furazan, furoxan)

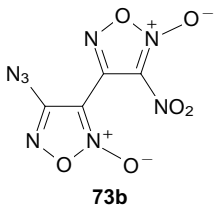
This method was applied, in particular, to prepare energetic 3-nitrobifuroxans **73a – c** containing explosophores at the second furoxan ring[94] and isomeric (4-nitrofurazan-3-yl)-nitrofuroxans **73d** and **74d**.[95] Bifuroxans

Structures 73a – d, 74d



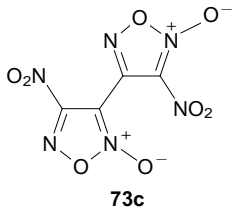
73a

m.p. 119 – 120°C,
ΔH_f° = 330.4 kJ mol^{-1},
Ω_{CO_2} = –26.67%



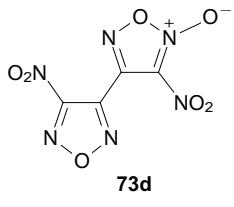
73b

Liqiud,
ΔH_f° = 529.7 kJ mol^{-1},
Ω_{CO_2} = –12.50%



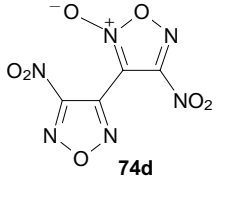
73c

m.p. 84 – 86 °C,
ΔH_f° = 421.2 kJ mol^{-1},
Ω_{CO_2} = 0



73d

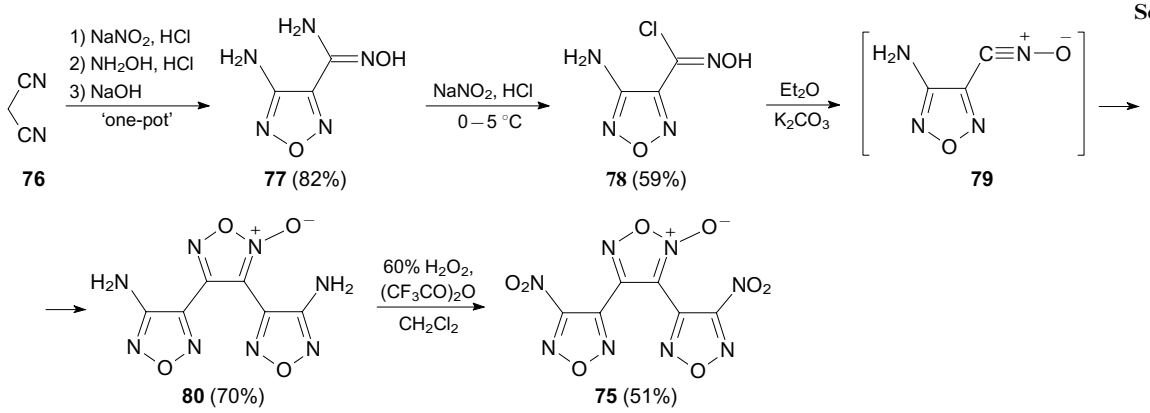
ΔH_f° = 417.5 kJ mol^{-1},
d = 1.92 g cm^{-3},
V_D = 9180 m s^{-1},
T_{dec} = 146 °C



74d

ΔH_f° = 417.5 kJ mol^{-1},
d = 1.934 g cm^{-3},
V_D = 9230 m s^{-1},
T_{dec} = 140 °C

Scheme 21



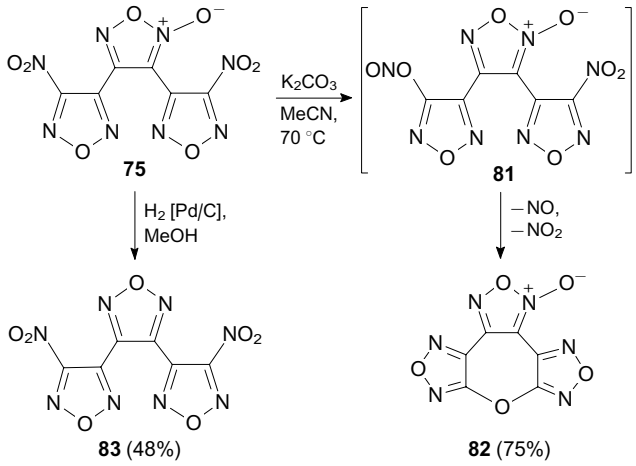
73a – c have high enthalpy of formation and a good oxygen balance (particularly, compound **73c**) but are unfortunately insufficiently stable. Furazanylfuroxans **73d** and **74d** are more thermally stable ($T_{dec} \geqslant 140$ °C). They have high densities ($d \geqslant 1.92$ g cm^{-3}), enthalpies of formation (417.5 kJ mol^{-1}) and detonation velocities (9180 and 9230 m s^{-1}, respectively) and are considered as powerful explosives. However, their sensitivity to shock and friction is rather high and similar to the corresponding parameters of glycerin trinitrate.

3,4-Bis(3-nitrofurazan-4-yl)furoxan (**75**) is a more promising furoxan- and furazan-containing nitro compound.[96] This low-melting compound (m.p. = 108 – 109 °C) advantageously combines high energy characteristics ($d = 1.937$ g cm^{-3}, $\Delta H_f^\circ = 706.1$ kJ mol^{-1}, $V_D = 9250$ m s^{-1}) and satisfactory sensitivity to shock and friction.[97,98] It compound is of interest as a substitute for TNT and other low-melting energetic compounds (in particular, trinitroazetidine) in explosive formulations.[99] Compound **75** is synthesized starting from malononitrile (**76**), which is transformed into 4-aminofurazan-3-carboxamidoxime (**77**) in a three-step one-pot process. The treatment of amidoxime **77** with the $NaNO_2$ – HCl system gives aminofurazanylhydroxamic acid chloride (**78**). The latter servers as a source of nitrile oxide **79**, which undergoes dimerization (without isolation) giving 3,4-bis(aminofurazanyl)furoxan (**80**). Target compound **75** was prepared in 51% yield by the oxidation of diamine **80** with 60% H_2O_2 in trifluoroacetic anhydride (Scheme 21).[100]

Nitro groups in nitro compound **75** are easily replaced by different nucleophiles (azide, amino, thiol or hydroxy groups). These reactions can occur in an intramolecular fashion. Thus, the treatment of compound **75** with K_2CO_3 affords cyclic ether oxepinotrioxadiazole **82**.[101] In the authors' opinion, one nitro group in compound **75** is rearranged into the nitrite group under the reaction conditions. The resulting nitrite **81** eliminates NO to form hydroxide anion, which is followed by intramolecular nucleophilic displacement of the second NO_2 group to give product **82**. Catalytic hydrogenation of **75** affords dinitrotrifurazanyl **83**, which is inferior in energy properties to 3,4-bis(nitrofurazanyl)furoxan **75**[102] (Scheme 22).

Therefore, in terms of the energy properties, nitro derivatives of furazan and furoxan can be considered as promising components of energetic formulations. They are characterized by a high nitrogen content, high density and good oxygen balance. Drawbacks of many compounds of this series are low thermal and chemical stability and high sensitivity to mechanical stimuli. However, some compounds, *e.g.* 3,4-bis(nitrofurazanyl)furoxan **75** and cyclic structures on its basis, satisfy the required parameters and can be useful as insensitive low-melting ESs.

Scheme 22

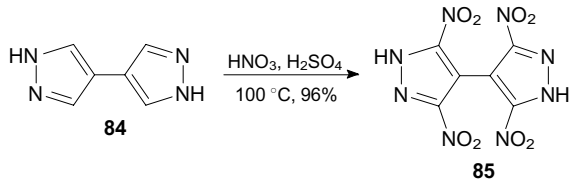


2.2.2. Nitropyrazoles

Since the enthalpy of formation of nitro derivatives of pyrazole (105.4 kJ mol^{-1}) is much lower compared to nitro derivatives of tetrazole (237.1 kJ mol^{-1}) and is slightly lower than that of 1,2,4-triazole derivatives (108.7 kJ mol^{-1}), nitropyrazoles have attracted little attention as energetic compounds for a long time. However, in recent years it became evident that the advantages of this type of compounds are a large number of reactive sites for introducing explosophores and the possibility of functionalization of these sites through electrophilic substitution, in particular nitration, the most commonly used approach in the synthesis of energetic compounds. Besides, pyrazoles differ from NH-azoles in that they can form stable *N*-nitro derivatives, thereby offering new possibilities for the synthesis of EMs.[103 – 105]

4-Nitropyrazole has been known since the mid-19th century; however, its 3-nitro isomer and 3,4- and 3,5-dinitropyrazoles were synthesized as late as the 1970s.[106] In 1998, Shevelev and co-workers[107] reported the synthesis of 3,3′,5,5′-tetranitro-4,4′-bipyrazole (**85**), the first representative of fully *C*-nitrated *N*-unsubstituted bipyrazoles, by the direct nitration of bipyrazole **84** (Scheme 23). A mixture of concentrated HNO_3 and H_2SO_4 proved to be the nitrating agent of choice. This mixture made it possible to perform the one-step introduction of four nitro groups at

Scheme 23



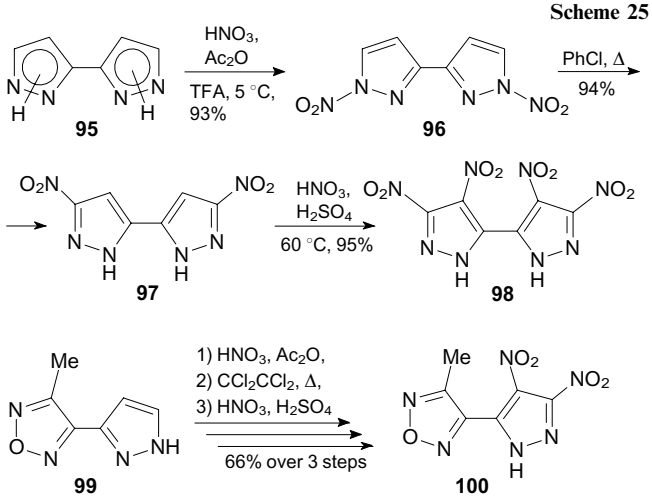
positions 3 and 5, which are usually not subjected to electrophilic attack, resulting in the formation of the target product in 96% yield. Recently, Klapötke and co-workers[108] showed that this reaction can give, apart from tetranitrobipyrazole **85**, mono-, di- and trinitropyrazoles depending on the conditions.

The direct acidic nitration of 4-substituted pyrazoles at positions 3 and 5 can be applied to prepare assemblies of nitropyrazole-containing heterocycles.[109, 110] Key substrates **90** and **91** were synthesized by successive reactions, including double formylation of the activated CH_2R group in compounds **86** and **87** followed by the transformation of diformylmethane derivatives **88** and **89** to the target pyrazole derivatives (Scheme 24). The nitration of assemblies **90** and **91** with a sulfuric – nitric acid mixture at 100 °C gave fully nitrated compounds **92** – **94**.

Isomeric 3,3′,4,4′-tetranitro-5,5′-bipyrazole (**98**) was synthesized using a bypass approach, which involves the *N*-nitration of bipyrazole **95** with acetyl nitrate, the thermal rearrangement of the resulting *N*,*N*′-dinitropyrazole **96** into *C*,*C*′-dinitropyrazole **97** and the nitration of the latter with a mixture of concentrated H_2SO_4 and HNO_3 at 60 °C (Scheme 25). The overall yield of **98** over three steps was 83%.[111 – 113] The generality of the method was demonstrated in relation to the synthesis of 3(5)-furazanyl-substituted 4,5(3)-dinitropyrazole **100** from bicyclic compound **99** according to a similar scheme.[114]

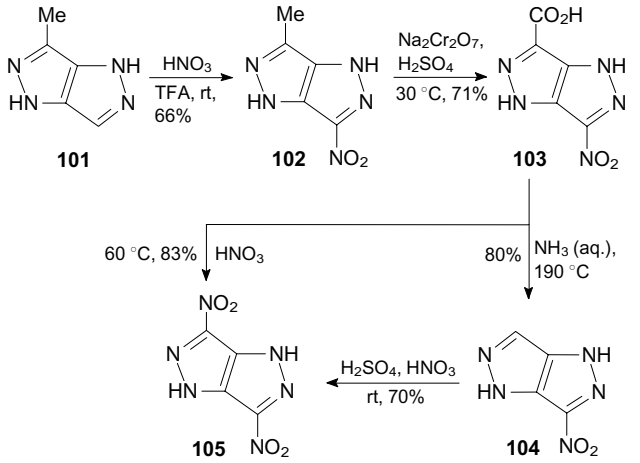
Annulated pyrazole derivatives can also be subjected to nitration. The nitration of 3-methylpyrazolo[4,3-*c*]pyrazole (**101**) at position 6 occurs even at room temperature in a mixture of HNO_3 and CF_3CO_2H.[115] The oxidation of the methyl group in compound **102** to the carboxyl group ($Na_2Cr_2O_7/H_2SO_4$) and the subsequent thermal decarboxylation of compound **103** afforded 3-nitropyrazolo[4,3-*c*]-pyrazole (**104**) (Scheme 26). The treatment of compound **104** with a sulfuric – nitric acid mixture gave fully *C*-nitrated pyrazolopyrazole (**105**). Later, it was shown that carboxylic acid **103** can be directly transformed into **105** by the treatment with 100% HNO_3, which makes it possible to do

Scheme 25

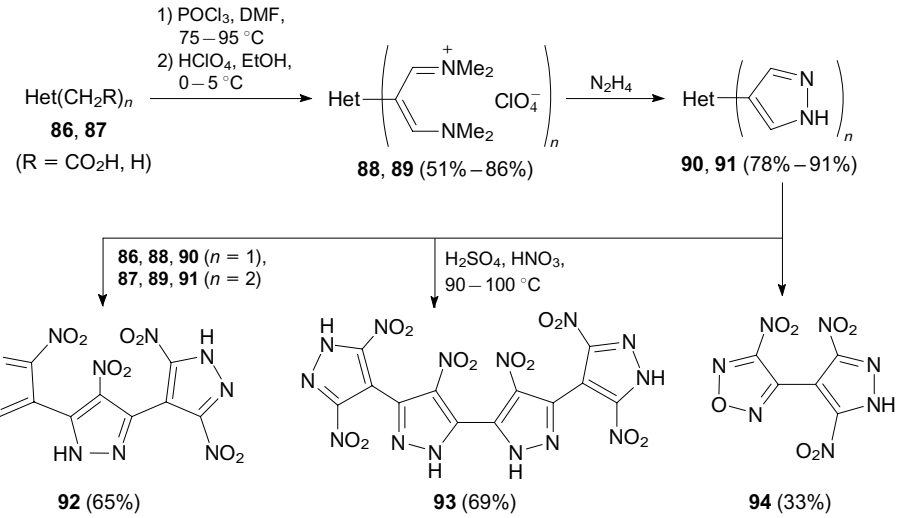


TFA is trifluoroacetic acid

Scheme 26



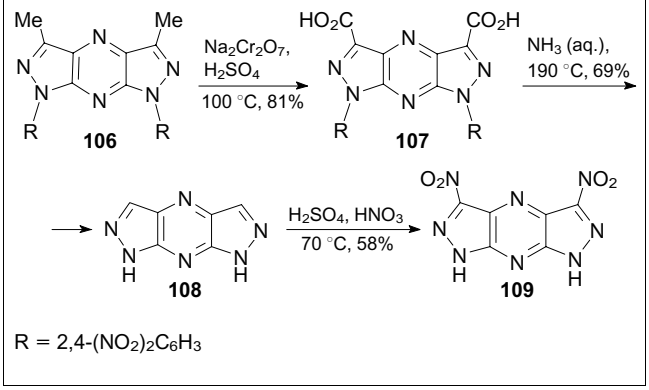
Scheme 24



without thermal decarboxylation and results in a substantially higher yield of the product.[116, 117] Compound **105**, being somewhat less energy efficient than HMX, is highly thermally stable (T_{dec} = 336 °C) and less sensitive to mechanical stimuli. Hence, salts of **105** with nitrogen-rich cations [116] and derivatives containing explosophoric groups (NO_2, NH_2, OH, CH_2ONO_2, CH_2N_3) at the endocyclic nitrogen atom [117–119] were synthesized and characterized.

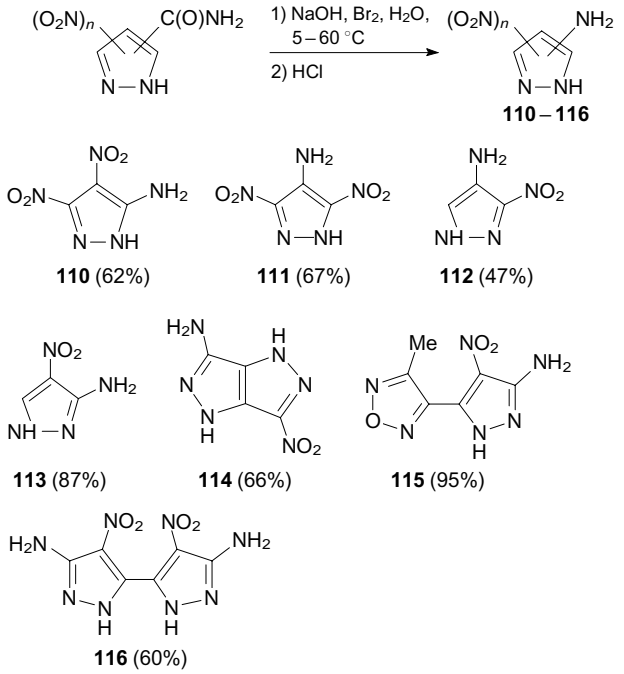
A similar approach proved to be useful for the synthesis of 3,5-dinitrodipyrazolo[3,4-*b*;4′3′-*e*]pyrazine (**109**).[120] The oxidation of methyl groups in *N*-protected substrate **106** afforded dicarboxylic acid **107**. The decarboxylation of **107** in aqueous ammonia accompanied by deprotection gave unsubstituted tricyclic compound **108**. The nitration of the latter with a sulfuric–nitric acid mixture produced dinitro derivative **109** with a high density (d = 1.85 g cm^{-3}) and high thermal stability (T_{dec} = 305 °C) (Scheme 27).

Scheme 27



The development of methods for the synthesis of aminonitropyrazoles and investigations of their chemical properties have attracted great attention. These compounds are insensitive explosives and, simultaneously, valuable synthons for the preparation of this series of energetic compounds. In particular, a procedure was proposed for the introduction of an amino group at the carbon atom of the nitropyrazole ring based on the Hofmann rearrangement of nitro- and dinitropyrazolecarboxylic acid amides.[111, 115, 121–124] This method was applied to prepare isomeric aminodinitropyrazoles **110** and **111** (compound LLM-116) and a series of other mono- (**112**, **113**) and bicyclic pyrazoles (**114**–**116**) containing amino and nitro groups (Scheme 28).

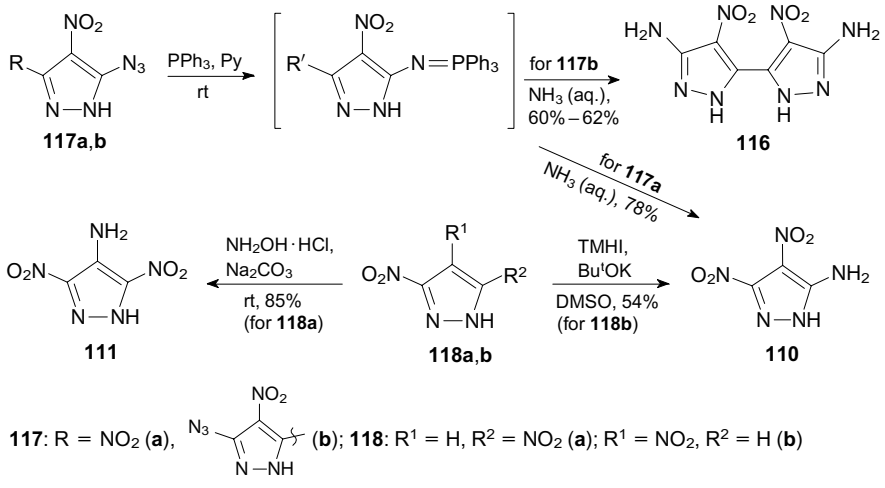
Scheme 28



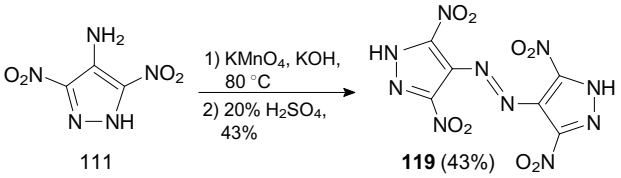
An alternative method for the synthesis of aminonitropyrazoles **110** and **116** is based on the hydrolysis of phosphazenes, derived from appropriate azidonitropyrazoles **117**, with aqueous ammonia [111, 125] (Scheme 29). Besides, the amino group can be directly introduced into dinitropyrazoles **118** *via* vicarious nucleophilic substitution of hydrogen with trimethylhydrazinium iodide (TMHI), hydroxylamine or 4-amino-1,2,4-triazole in the presence of strong bases.[126–129] Compounds **110** and **111** are produced in 54%–85% yields.

The presence of two nitro groups in compounds **110** and **111** reduces the reactivity of the amino group; however, it can be involved in oxidative transformations giving new energetic compounds. For instance, the oxidation of the amino group in pyrazole **111** with $KMnO_4$ in an alkaline medium gave 4,4′-azodipyrazole **119**, although in low yield (Scheme 30).[130]

Scheme 29

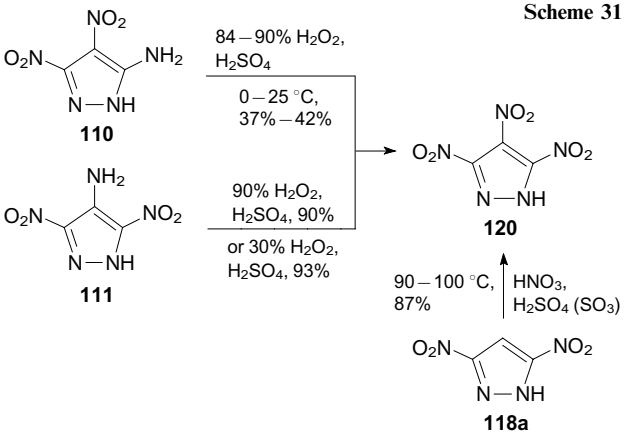


Scheme 30



Dalinger's research team [131] and Herve *et al.*[132] independently synthesized 3,4,5-trinitropyrazole (**120**), which is the first and as yet the only representative of thermally stable NH-azoles fully nitrated at carbon atoms, by the oxidation of aminodinitropyrazoles **110** and **111** with 90% H_2O_2 in concentrated H_2SO_4 (Scheme 31). Almost at the same time, Shreeve and co-workers [133] found that the oxidation of amine **111** to nitro derivative **120** in the presence of less hazardous 30% H_2O_2 is also very efficient (93% yield). Besides, Dalinger *et al.*[134] and Herve and co-workers [132] proposed a practical method for the synthesis of product **120** by the nitration of 3,5-dinitropyrazole (**118a**) with a mixture of concentrated nitric and sulfuric acids, in particular, in the presence of fuming sulfuric acid (oleum), at 90 – 100 °C. 3,4,5-Trinitropyrazole is a stable non-hygroscopic energetic compound. Its stable and safe-to-handle salts with nitrogen-rich bases (guanidine, amino-, diamino-, triaminoguanidine, 4-amino- and 3,5-diamino-1,2,4-triazole, *etc.*) are comparable in terms of thermodynamic and detonation properties (P_D = 23.7 – 31.9 GPa; V_D = 7580 – 8540 m s^{-1}) with 1,3,5-triamino-2,4,6-trinitrobenzene (TATB).[133]

Scheme 31

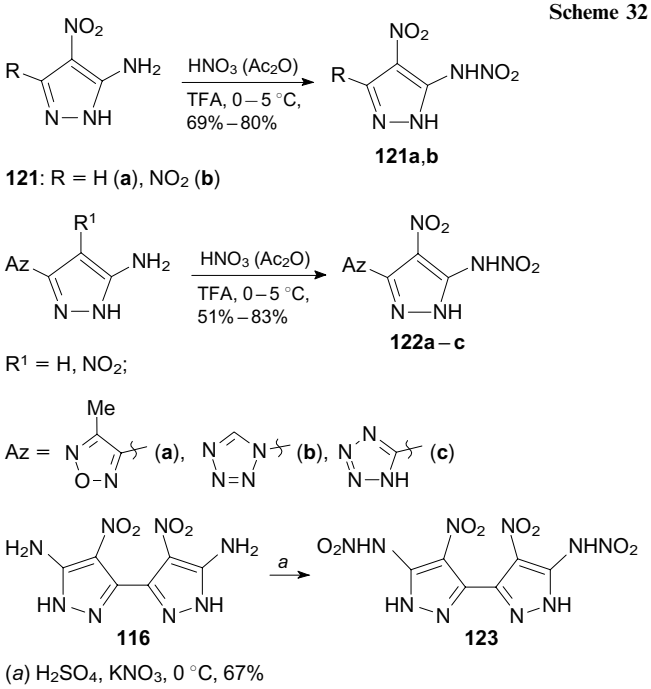


Shevelev and co-workers [122, 123] found that the nitration of simplest aminonitro- and aminodinitropyrazoles with acetyl nitrate affords stable *N*-nitramines **121** (Scheme 32). This method is also applicable to the synthesis of primary nitramines **122** in series of hetaryl-substituted nitropyrazoles [124, 135] and bis(nitramino)dipyrazole **123**.[111, 136]

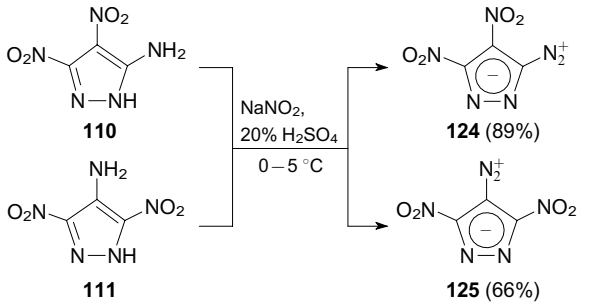
Despite low basicity of the amino group, isomeric aminodinitropyrazoles **110** and **111** easily undergo diazotization with nitrous acid, which is generated *in situ* from $NaNO_2$ and 20% H_2SO_4, to form stable zwitterionic diazodinitropyrazoles **124** and **125**, respectively (Scheme 33).[123, 137]

The diazonium group in diazodinitropyrazole **125** remains intact under the action of nucleophiles (N_3^- or Br^- ions), which replace one nitro group in the pyrazole ring to form compounds **126** (Scheme 34).[123] Under more severe conditions (110 °C), both nitro groups in compound **125** can be replaced by pyrazolate anions. This reaction affords 3,5-bis(4′-amino-3′,5′-dinitropyrazol-1′-yl)-4-diazopyrazole (**127**) (compound LLM-226). Compound **127** is characterized by remarkably high thermal stability (T_{dec} = 278 °C) as compared with other diazo compounds. It should be noted that sensitivity of **127** to mechanical stimuli is comparable to that of HMX,[138] while diazo substrate **125** is an primary explosive.[139]

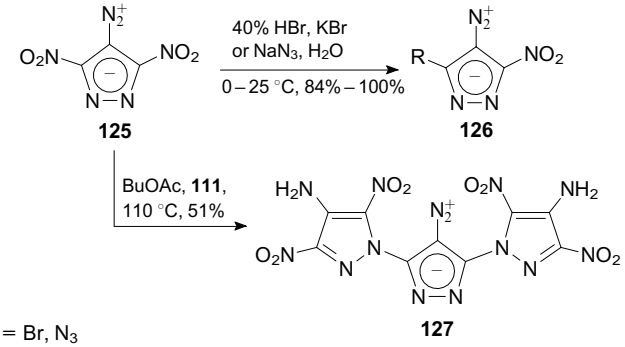
Scheme 32



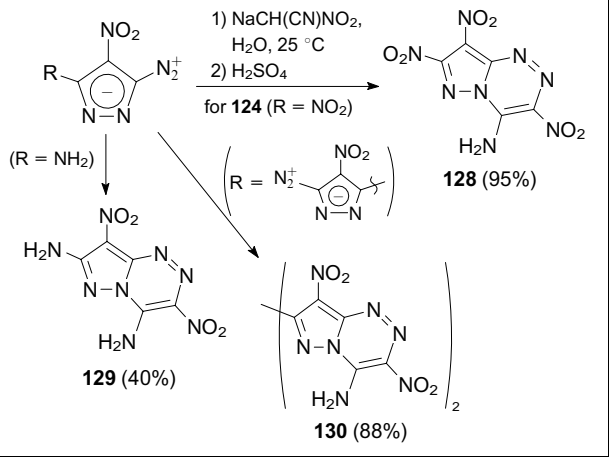
Scheme 33



Scheme 34



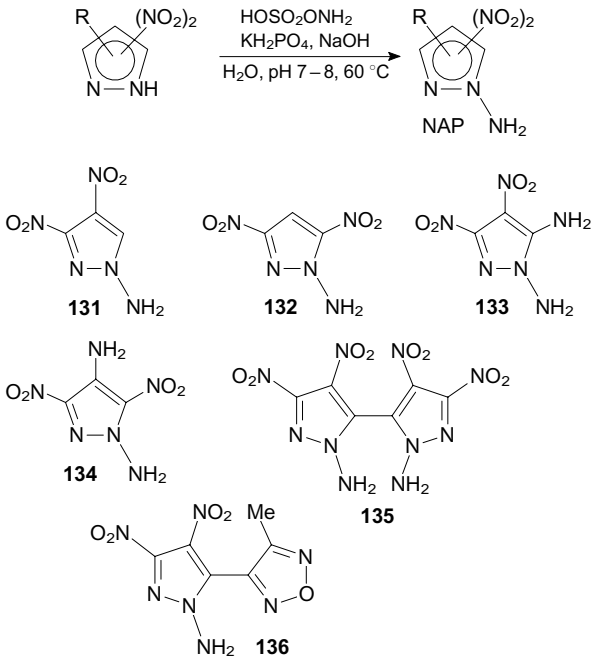
Scheme 35



In some cases, diazodinitropyrazoles can be used to prepare energetic polycyclic compounds, in which the pyrazole ring is annulated with other heterocycles. Thus, the condensation of diazopyrazole **124** with $NaCH(CN)NO_2$ affords 4-amino-3,7,8-trinitropyrazolo[5,1-*c*][1,2,4]triazine **128** (Scheme 35).[123] In terms of energetic performance, this compound is comparable with HMX, but it is less sensitive to mechanical stimuli and is more thermally stable.[126] Recently, this approach was successfully applied to prepare analogues **129** and **130**, which are also characterized by high thermal stability (T_{dec} = 315 – 355 °C).[140, 141]

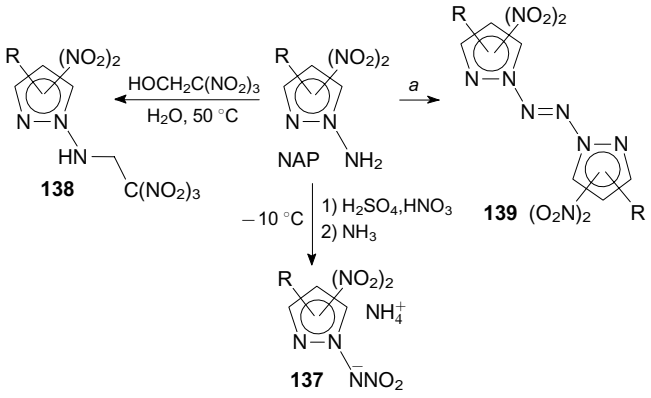
A promising approach to the energetic functionalization of *C*-polynitropyrazoles is based on the *N*-amination. Shevelev and co-workers[142] described an efficient method for the synthesis of *N*-aminonitropyrazoles (NAP) by the reaction of *in situ* generated nitropyrazolate anions with the simple and available aminating agent hydroxylamine-*O*-sulfonic acid (Scheme 36). The reaction occurs in an aqueous buffer, with maintaining the required concentration of nitropyrazolate anions.[143] The generality of the method was demonstrated by the synthesis of a wide range of *N*-aminonitropyrazoles, in particular compounds **131** – **136**.[112, 143 – 146] Besides, NAPs can be synthesized by the treatment of nitropyrazolate salts with other aminating agents (*O*-picryl- and *O*-tosylhydroxylamines) in MeCN.[112, 132, 147, 148]

Scheme 36

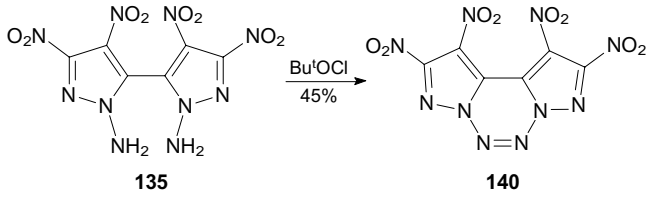


N-Aminopyrazoles are precursors for the synthesis of energetic compounds containing an exocyclic N – N bond. For instance, Shreeve and co-workers used nitration, trinitroethylation and oxidation reactions to synthesize *N*-nitro (**137**),[144] *N*-trinitroethyl (**138**)[148] and aza derivatives (**139**)[149] of NAPs (Scheme 37). The oxidation of *N*,*N*′-diaminodipyrazole **135** with *tert*-butyl hypochlorite gave a new energetic compound, 1,2,9,10-tetranitrodipyrazolo[1,5-*d*:5′,1′-*f*][1,2,3,4]tetrazine (**140**).[112]

Scheme 37



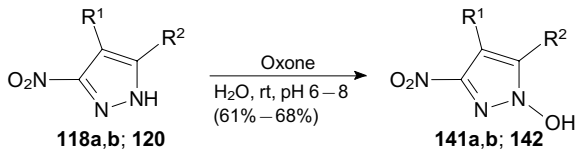
(*a*) SDCl, AcOH, – 10 °C; **137**: R = H, $\bar{N}NO_2NH_4^+$ (52 – 76% yield);
138: R = H, N_3, NH_2 (52% – 71%); SDCl is sodium dichloroisocyanurate
139: R = H, N(NO2)Me (41% – 62%)



Dalinger and co-workers[150] developed a method for the direct *N*-hydroxylation of nitropyrazoles by the oxidation of their anions with potassium peroxymonosulfate (oxone) in aqueous buffer. Later, this approach was successfully applied to prepare *N*-hydroxy derivatives of di- and trinitropyrazoles, in particular compounds **141a**,**b** (Ref. 151) and **142** (Ref. 152) (Scheme 38).

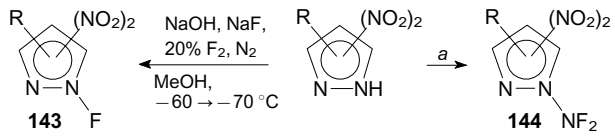
Shevelev and co-workers[153] reported facile synthetic approaches to polynitropyrazoles containing an N – F bond. They found that the treatment of polynitropyrazole

Scheme 38

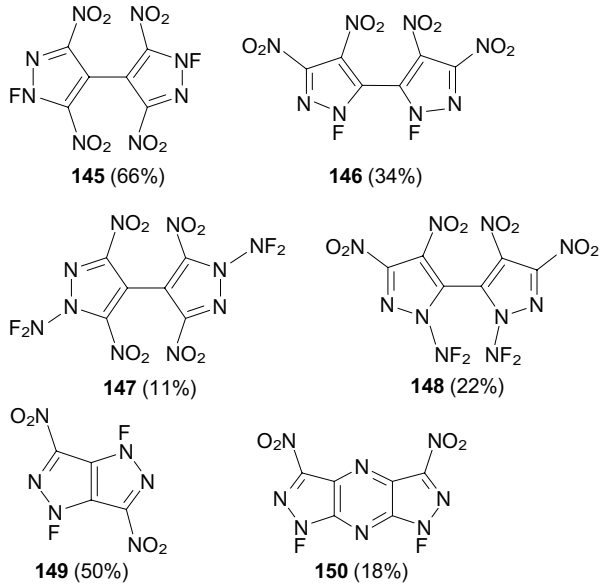


118, **141**: R^1 = H, R^2 = NO_2 (**a**); R^1 = NO_2, R^2 = H (**b**);
120, **142**: R^1 = R^2 = NO_2; Oxone is potassium peroxymonosulfate

Scheme 39



(*a*) $NaHCO_3$, F_2NOSO_2F, PEG-400, H_2O, EG, DCE, −20 °C (5% – 80% yield); R = H, Cl, CN, Pic; EG is ethylene glycol, PEG is polyethylene glycol; DCE is 1,2-dichloroethane

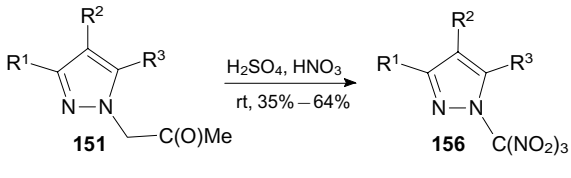


sodium salts with a 10% F_2/N_2 gas mixture gives *N*-fluoronitropyrazoles **143** (Scheme 39). The treatment of the same substrates with *O*-fluorosulfonyl-*N*,*N*-difluorohydroxylamine affords *N*-difluoroamino derivatives **144**.[154] This approach allowed the synthesis of energetic compounds **145** – **148** containing two bridged dinitropyrazole rings and annulated polynitrogen systems **149** (compound LLM-120) and **150**.

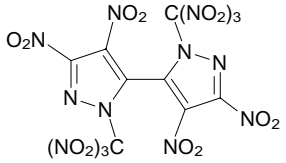
A facile method for *N*-functionalization of nitropyrazoles with energetic groups involves the destructive nitration of *N*-acetonylpyrazoles **151** with sulfuric – nitric acid mixtures. This reaction performed in the presence of water affords *N*-(dinitromethyl)nitropyrazoles **152**.[155 – 157] Due to the ability of the dinitromethyl group to be involved in reactions with electrophilic reagents, the latter compounds are key precursors for the synthesis of energetic compounds **153** – **155** containing a fluoro- or difluoroaminodinitromethyl group[155, 158] and some other explosophores at the nitrogen atom of the pyrazole ring (Scheme 40).[159]

The destructive nitration of compound **151** with concentrated H_2SO_4/HNO_3 mixtures does not stop at the formation of *N*-dinitromethyl derivatives **152** but produces *N*-trinitromethylnitropyrazoles **156** (Scheme 41).[158, 160 – 162] The presence of the trinitromethyl group significantly increases the oxygen content of the molecule and also increases the density of the compound (by 0.10 – 0.15 g cm^{-3}). This method was used to synthesize compound **157** containing ten nitro groups, which is among the three leading CHNO-containing oxidants with the highest density (d = 2.021 g cm^{-3}).[163]

Scheme 41



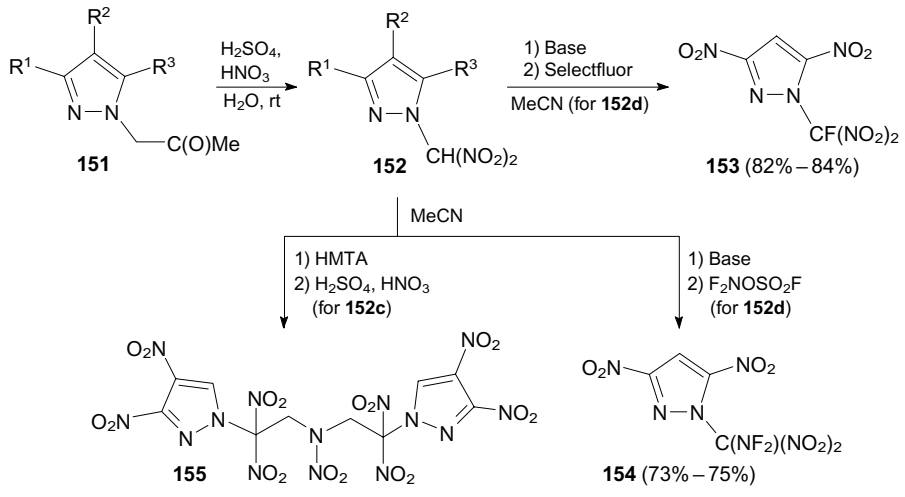
$R^1 = R^3 = H$, $R^2 = NO_2$ (**a**); $R^1 = R^2 = NO^2$, $R^3 = H$ (**c**); $R^1 = R^3 = NO_2$, $R^2 = H$ (**d**)



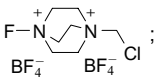
157 (71%)

Therefore, polynitro derivatives of pyrazole are promising compounds, which combine high energy parameters with satisfactory thermal stability and sensitivity to mechanical stimuli. The developed procedures for *C*- and *N*-functionalization of polynitropyrazoles enable the synthesis of various energetic compounds of this class with a wide range of explosophores, including positional isomers. The latter fact is important for structure – property relationship analysis and the creation of new lines of research in this area.

Scheme 40



151, **152**: $R^1 = R^3 = H$, $R^2 = NO_2$ (**a**); $R^1 = NO_2$, $R^2 = R^3 = H$ (**b**); $R^1 = R^2 = NO_2$, $R^3 = H$ (**c**); $R^1 = R^3 = NO_2$, $R^2 = H$ (**d**);

Selectfluor = ;

HMTA is hexamethylenetetramine

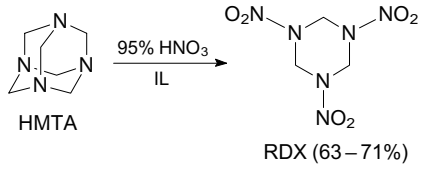
2.3. Environmentally friendly methods for the synthesis of energetic nitro compounds

Basic components of EMs are generally synthesized by the nitration of appropriate hydrocarbons, alcohols and amine derivatives. In industry, these reactions are usually performed in the presence of a large excess (5 – 10-fold) of a nitric – sulfuric acid mixture, which simultaneously serves as the nitrating agent and the reaction medium. Nitration processes are explosion dangerous and environmentally hazardous, because they are accompanied by the formation of huge amounts of acidic waste products, which are difficult to dispose of.[164] The promising approach to addressing these issues is the application of green chemistry methods for the preparation of EMs [103, 165 – 167] based, in particular, on the use of ionic liquids (IL) and liquefied gases (CO_2 and Freons), including in the supercritical (sc) state, as the reaction media. These stable and virtually nonflammable media make nitration reactions much less explosion and fire hazardous.[5, 168, 169] Besides, their adverse environmental impacts are also considerably reduced. This Section considers selected results obtained in this promising research area in recent years.

2.3.1. Synthesis of nitro compounds in an ionic liquid medium

Ionic liquids modified with Brønsted acid moieties (in particular, with sulfo groups) can be utilized as solvents and catalysts in the synthesis of energetic nitro compounds. These ionic liquids catalyze nitration reactions facilitating the formation of nitronium cations and enabling the synthesis of polynitro compounds, which are dangerous to handle (they explode on heating, shock and friction), under milder conditions and in higher yields compared to known methods. For instance, the nitrolysis of hexamethylenetetramine (HMTA) with 95% HNO_3 in acidic IL (imidazolium and pyridinium salts containing sulfo groups in the side chain) affords RDX (Scheme 42). The best results were obtained using *N*-(4-sulfo-n-butyl)pyridinium nitrate [SO_3H-bpyr][NO_3], which gave RDX in a yield 10% higher than that achieved in the absence of IL.[170]

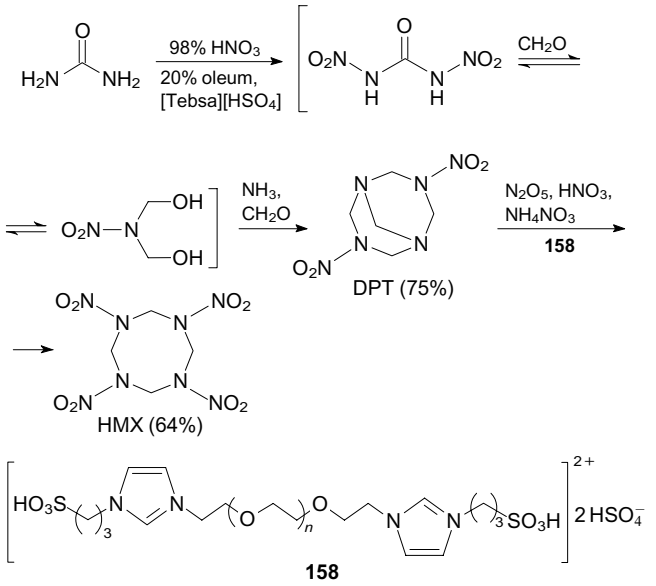
Scheme 42



IL = [hmim]X or [SO_3H-pmim]X or [SO_3H-bpyr]X (X = OTs, NO_3, OTf); hmim is 1-(n-hexyl)-3-methyl)imidazolium, pmim is 1-propyl-3-methylimidazolium, bpyr is 1-(n-buthyl)pyridinium

Sulfo-modified dicationic acidic IL **158** based on polyethylene glycol PEG-200 proved to be efficient in the synthesis of HMX from 3,7-dinitro-1,3,5,7-tetraazabicyclo[3.3.1]nonane (DPT) (Scheme 43).[171] Fuming nitric acid (a mixture of N_2O_5 and 100% HNO_3) – NH_4NO_3 served as the nitrating agent. In the presence of **158**, the yield of HMX was 64%. It is worth noting that the key precursor DPT can be synthesized by the nitration of urea with fuming nitric acid in the presence of another ionic liquid, *N*-(4-sulfonic acid) butyl triethylammonium hydrosulfate [Tebsa][HSO_4].[172]

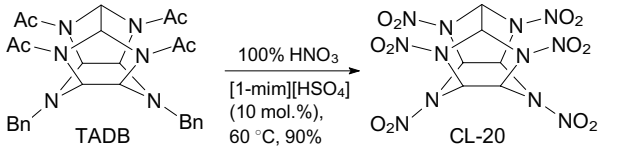
Scheme 43



Tebsa is triethyl(4-sulfo-*N*-butyl)ammonium

The acidic IL 1-methylimidazolium hydrogen sulfate ([1-mim][HSO_4]) promotes the synthesis of CL-20 from 2,4,6,8-tetraacetyl-10,12-dibenzyl-2,4,6,8,10,12-hexaazaisowurtzitane (TADB) (Scheme 44). Under the optimal conditions (excess fuming nitric acid and the temperature of 60 °C), the yield of the product CL-20 was 90%.[173] The ionic liquid was not decomposed under very severe nitration conditions and could be reused without the loss of efficiency of the process.

Scheme 44



1-mim is 1-methylimidazolium

Acidic groups that are present in IL also promote the nitration of other annulated polynitrogen heterocycles. For instance, 2,5,7,10-tetraazabicyclo[4.4.0]decane (TAD) is easily nitrated to 2,5,7,10-tetranitro-2,5,7,10-tetraazabicyclo[4.4.0]decane (TNAD) with N_2O_5 in the presence of only 3 mol.% 1-(4′-SO_3H-n-butyl)-3-methylimidazolium hydrogen sulfate ([SO_3H-bmim][HSO_4]) (Scheme 45).[174]

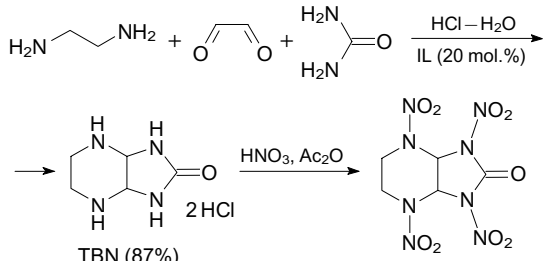
Scheme 45



bmim is 1-(n-butyl)-3-methylimidazolium

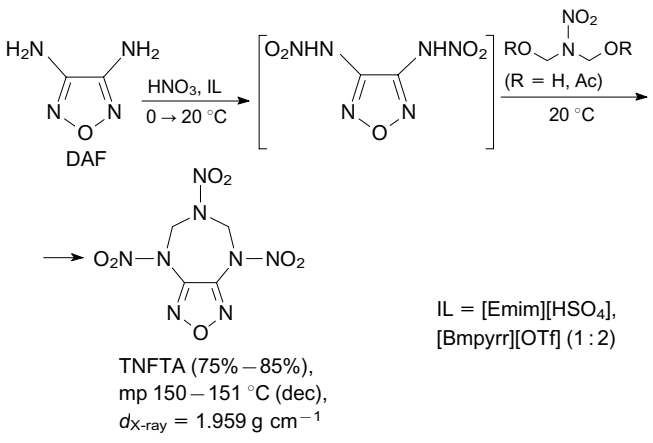
In some cases, ILs facilitate the formation of polycyclic amines serving as substrates for nitration reactions. For example, 2,5,7,9-tetraazabicyclo[4.3.0]nonan-8-one dihydrochloride (TBN), which is a direct precursor of explosophoric 2,5,7,9-tetranitro-2,5,7,9-tetraazabicyclo[4.3.0]-nonan-8-one (TNTBN), was synthesized by the three-component condensation of ethylenediamine, glyoxal and urea catalyzed by trimethyl-(3-SO_3H-n-propyl)ammonium hydrogen sulfate (([TMPSA][HSO_4]).[175] The nitration of TBN with a mixture of nitric acid and acetic anhydride gives TNTBN in a rather high yield (Scheme 46). In this case, IL can also be regenerated and reused.

Scheme 46



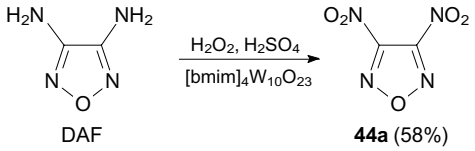
The bicyclic furazan derivative, 4,6,8-trinitro-5,6,7,8-tetrahydro-4*H*-furazano[3,4-*f*][1,3,5]triazepine (TNFTA), annulated with the fully nitrated triazepine ring was synthesized from the available diamine DAF in an acidic liquid acid medium (Scheme 47). The method is based on the one-pot reaction sequence involving the nitration of DAF with the HNO_3 – IL system and the condensation of the *in situ* produced 3,4-di(nitramino)furazan with 2-nitroazapropane-1,3-diol or its acetate.[176] The highest yield of TNFTA in the tandem reaction (up to 85%) was achieved when using two-component IL containing 1-ethyl-3-methylimidazolium hydrosulfate [Emim][HSO_4] and 1-butyl-1-methylpyrrolidine triflate [Bmpyrr][OTf] in a ratio of 1 : 2.

Scheme 47



Substrate-specific ILs catalyze not only the nitration of amines but also the oxidation of primary amino groups to nitro groups. For instance, in the presence of 1-methyl-3-butylimidazolium decatungstate [bmim]$_4$[$W_{10}O_{23}$] (0.2 mol.%), DAF is transformed into the energetic oxidant 3,4-dinitrofurazan (**44a**) under the action of a mixture of concentrated H_2SO_4 and 50% H_2O_2 (2 : 3) (Scheme 48).[177] It should be noted that the reaction performed in the presence of the commonly used catalyst ($Na_2WO_4 \cdot 2H_2O$) instead of IL gave **44a** in substantially lower yield (39%).

Scheme 48

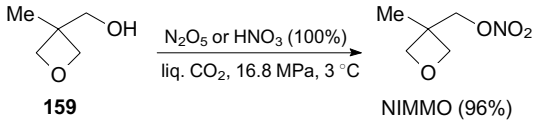


2.3.2. Synthesis of nitro compounds in liquefied gases

Some available, non-toxic and stable liquefied gases in the liquid or sc state can also be used as environmentally friendly reaction media for the synthesis and modification of energetic compounds. Carbon dioxide, a natural gas emitted in huge amounts by thermal power stations upon combustion of hydrocarbon fuels, is most promising for this purpose. Some fluorohydrocarbons, allowed to use as refrigerants in commercial refrigerators, in particular 1,1,1,2-tetrafluoroethane (TFE), which have no destructive effect on the ozone layer and do not cause acid precipitations,[178] have also attracted research attention in recent years. These compounds are chemically stable, non-flammable, can be easily separated from the products by simple decompression and can recycle in engineering processes.

The first example of the nitration in liquefied CO_2 is apparently the synthesis of 3-nitroxymethyl-3-methyl oxetane (NIMMO), serving as a monomer for the preparation of an energetic polymer binder.[179] The addition of alcohol **159** to a solution of the nitrating agent (N_2O_5 or 100% nitric acid) in liquid CO_2 at 3 °C and a pressure of 16.8 MPa affords NIMMO in 96% yield (Scheme 49). Mild reaction conditions prevent partial oligomerization of the product (~10%), which is observed under standard conditions (CH_2Cl_2).

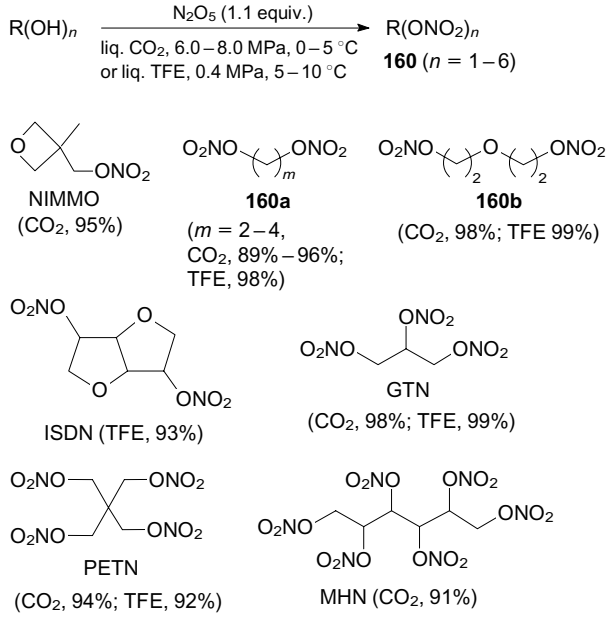
Scheme 49



To exclude a large excess of the nitrating agent in the first step of the exothermic reaction, it was proposed to perform the nitration by gradually adding a solution of N_2O_5 in liquid CO_2 to a solution or suspension of the alcohol in the same solvent.[180] Under these conditions, various alcohols were transformed into exhaustive nitration products **160** containing up to six nitrate groups in virtually quantitative yields, the excess of N_2O_5 being less than 10% per introduced nitro group (Scheme 50). This method was used to synthesize components of EMs and active pharmaceutical ingredients, in particular glycerin trinitrate (GTN), pentaerythritol nitrate (PETN), mannitol nitrate (MHN), *etc*.

1,1,1,2-Tetrafluoroethane (TFE) with an equilibrium vapour pressure (0.57 MPa at 20 °C) much lower that that of CO_2 (5.73 MPa at 20 °C) (see Scheme 50) proved to be an even more promising medium for the nitration of alcohols. The use of this medium enables the synthesis of

Scheme 50

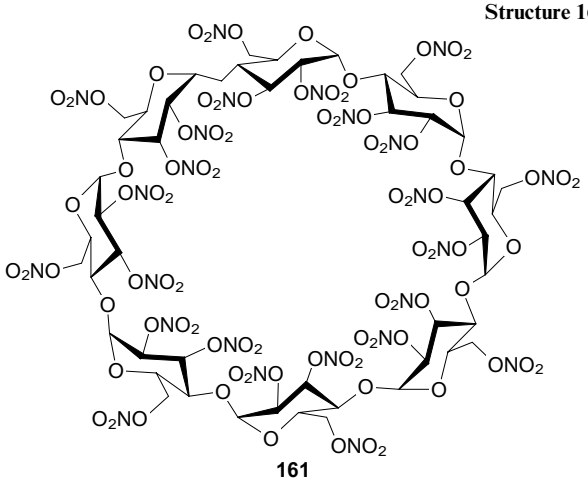


TFE is 1,1,1,2-tetrafluoroethane

nitrates **160** with the same output but at a much lower pressure,[181] which does not require specialized expensive equipment, thereby making the method technologically feasible.[182] Most recently, the continuous nitration of alcohols with N_2O_5 in a liquefied TFE flow was reported.[183] The flow installation is characterized by much higher performance (two orders of magnitude higher) compared with batch reactions. It prevents local overheat of the reaction mixture due to a high flow rate and a minimum amount of the reactants that are transferred to the reactor active zone per unit time. The recycling of TFE is low energy consuming. Freon is easily separated from the products at the reactor outlet by partial decompression (20 °C, 0.3 MPa) and is returned to the nitration step. Apparently, this is one of the safest and most environmentally friendly nitration processes highly promising for practical application.

High-molecular-weight alcohols can also be nitrated in liquefied gases. Thus, the treatment of γ-cyclodextrin composed of eight glucopyranose units and 24 hydroxy groups with dinitrogen pentoxide in liquid CO_2 affords polynitrate **161** with a 13.5% nitrogen content, which is similar to the theoretically possible value.[184] The distinguishing feature of the method is that the nitrating agent is generated from 100% HNO_3 and phosphoric anhydride or oleum ($H_2SO_4 \cdot SO_3$) in an auxiliary vessel in CO_2 (25 °C, ~10.0 MPa), and the resulting solution is passed through a special valve to the nitrating apparatus containing solid γ-cyclodextrin. The nitration is performed at −10 °C and 6.8 MPa in the presence of NaF to bind nitric acid that is released in the course of the reaction. Product **161** is formed in 91% yield. This compound is utilized as a substitute for nitrocellulose in smokeless gunpowders and CSRPs.[185]

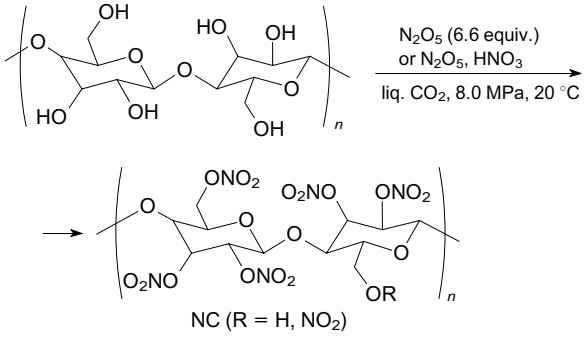
Structure 161



161

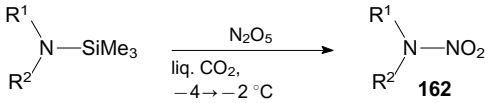
The natural polymer cellulose is also easily nitrated by dinitrogen pentoxide or fuming nitric acid in liquid CO_2 at 10 °C and a pressure of 8.0 MPa to form nitrocellulose NC (Scheme 51). Depending on the type of cellulose (cotton, linen, microcrystalline, *etc.*), composition and amount of the nitrating agent, and the reaction time (1 – 3 h), the nitrogen content in the NC product is 11.0 mass % – 13.8 mass %.[184, 186, 187] A mixture of HNO_3 and Ac_2O (1 : 1 – 1 : 5) can also be used as the nitrating agent;[188] however, N_2O_5 and fuming nitric acid are agents of choice because the reactions with these agents afford easily recoverable nitric acid as the only by-product. These results are important in terms of practical applications because nitrocellulose is a large-scale commercial product used for manufacturing gunpowders and materials for civilian applications (membranes, dyes, celluloids, *etc.*).[189]

Scheme 51



The *N*-nitration (nitration of silylamines with N_2O_5) in liquid CO_2 was reported for the first time at the Meeting on Supercritical Fluids (Nottingham, UK) in 1999 (Scheme 52).[190] However, under the proposed conditions, *N*-nitramines **162** were prepared in lower yield than in CH_2Cl_2.[191] Besides, explosion hazardous silyl nitrates were obtained as side reaction products.

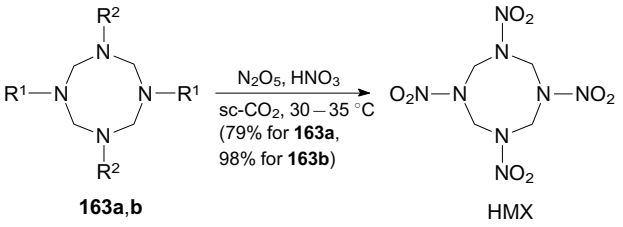
Scheme 52



$R^1 = R^2 = Me$ (62%); $R^1 – R^2 = (CH_2)_2O(CH_2)_2$ (68%)

Shortly after, US researchers patented a procedure for the synthesis of *N*-nitramines by the nitration of acylamides with dinitrogen pentoxide in liquid and sc-CO_2.[184] In particular, the authors reported the synthesis of HMX from 1,3,5,7-tetraacetyl-1,3,5,7-tetraazacyclooctane (**163a**) or 3,7-diacetyl-1,5-dinitro-1,3,5,7-tetraazacyclooctane (**163b**) in sc-CO_2 in 79% and 98% yields, respectively (Scheme 53).

Scheme 53

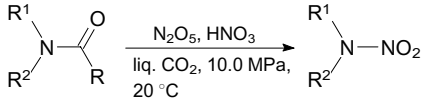


$R^1 = R^2$ = Ac (**a**); R^1 = Ac, $R^2 = NO_2$ (**b**); sc-CO_2 is supercritical CO_2

Unfortunately, the patented procedure does not include details required for the reproduction of the results.

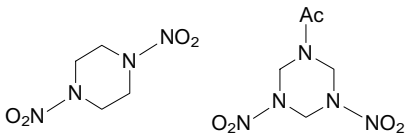
A thorough investigation of the nitrolysis of acylamides to *N*-nitramines **162** with N_2O_5 or fuming nitric acid in liquid CO_2 identified the N_2O_5 – 100% HNO_3 mixture (3 : 4) as the nitrating agent of choice (Scheme 54).[192] Under these conditions, a series of linear and cyclic *N*-nitramines, in particular *N*,*N*′-dinitropiperazine (**164**) as a component of smokeless CSRPs with a low burning velocity (95% yield), were synthesized.[193] However, attempts to introduce three nitramine groups into 1,3,5-triacetylhexahydro-1,3,5-triazine in liquid or sc-CO_2 failed. The reactions afforded dinitro compound **165** instead of RDX. This result is in contradiction with the data in the patent [184] and casts doubt on the possibility of preparing RDX and HMX in CO_2.

Scheme 54



162 (56% – 84%)

R = H, Me; $R^1 = R^2$ = Me, Et, Bu^n; $R^1 - R^2 = (CH_2)_2O(CH_2)_2$, $(CH_2)_5$

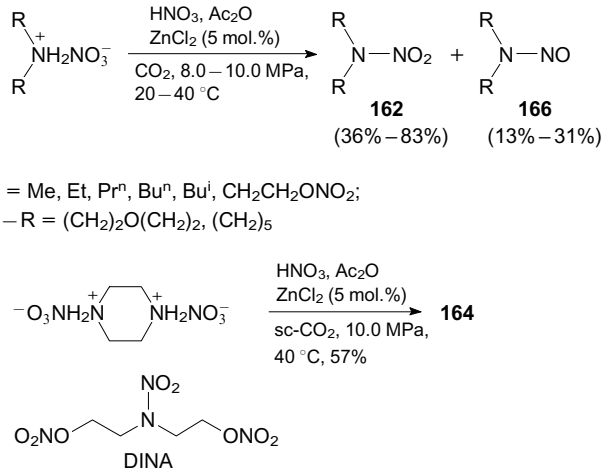


164 (95%) **165** (57%)

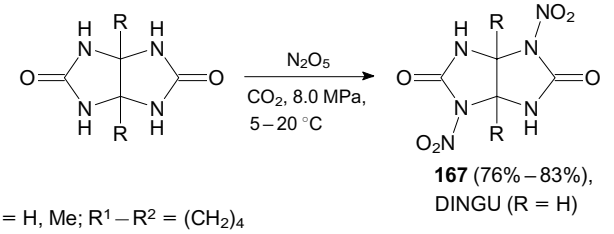
Disubstituted *N*-nitramines **162** can be synthesized by the catalytic ($ZnCl_2$) nitration of dialkylamine nitrates with a 100% HNO_3 – Ac_2O mixture in liquid or sc-CO_2 (Scheme 55).[194, 195] The reaction can be performed with aliphatic and heterocyclic amines. In particular, compound **164** and bis(nitroxyethyl)nitramine (DINA) are useful products. However, in some cases the reaction is complicated by the formation of nitrosamines **166** as by-products due to the presence of dinitrogen trioxide (N_2O_3) generated by the redox reaction of the catalyst with the reactants.

The nitration of glycoluril and its 3a,6a-disubstituted analogues with N_2O_5 (4.0 equiv.) in liquid CO_2 (8.0 MPa, 5 – 20 °C) gave dinitro compounds **167** with diagonal arrangement of nitro groups (Scheme 56),[196] in particular, the insensitive explosive 1,4-dinitroglycoluril (DINGU) (V_D = 7580 m s^{-1}, d = 1.99 g cm^{-3}). A similar reaction with 1,3-dimethylglycoluril afforded compound **168** containing both nitro groups in the same urea moiety. This method is applicable to the fluid nitration of hexahydroimidazo[4,5-*d*]imidazol-2(1*H*)-one. Like DINGU, the product of this reaction, 2,6,8-trinitro-2,4,6,8-tetraazabicyclo[3.3.0]octan-3-one (HK-55), having a rather high density (1.905 g cm^{-3}), is characterized by low shock sensitivity.[197]

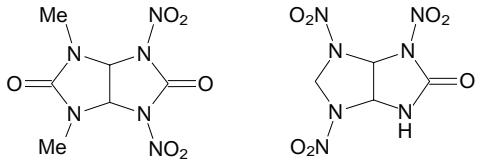
Scheme 55



Scheme 56

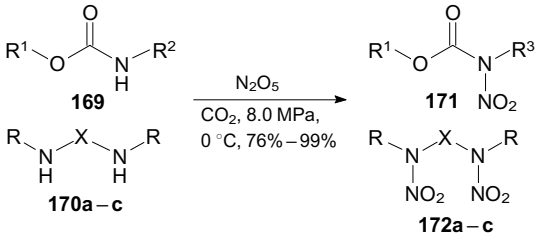


R = H, Me; $R^1 - R^2 = (CH_2)_4$



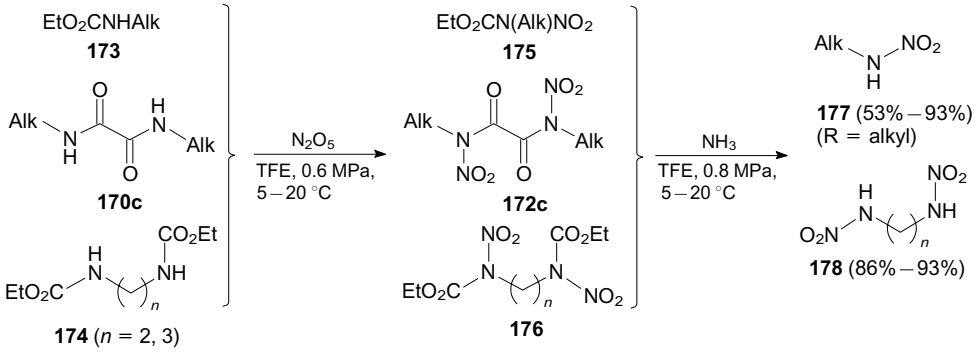
The treatment of *N*-alkyl carbamates **169** and *N*-alkylamides of carbonic, sulfuric and oxalic acids **170a – c** with N_2O_5 in liquid CO_2 gave the corresponding *N*-nitro compounds **171** and **172a – c** in high yields (Scheme 57).[198] Products **171** and **172** are precursors of primary *N*-nitramines, in particular of methylnitramine and bis-(*N*-nitramino)ethane, used to prepare practically important energetic systems.[199, 200] The advantage of this method is that it does not require environmentally hazardous nitrating

Scheme 57



$R^1 = R^2$ = Et; R^1 = Et, $R^2 = (CH_2)_2NHCO_2Et$; $R^1 - R^2 = (CH_2)_2$;
R = Me; R – R = $(CH_2)_2$;
X = C(O) (**a**); SO_2 (**b**); C(O)C(O) (**c**)

Scheme 58



agents containing sulfuric [201] or trifluoroacetic [202] acids and chlorinated solvents.[191]

N-Nitrourethanes and *N*-nitramides that are dangerous to handle (sensitive to shock and friction) are generally transformed into primary *N*-nitramines by alkaline hydrolysis [203] or ammonolysis.[204 – 206] Recently, Zlotin and coworkers [207, 208] developed a one-pot procedure for the synthesis of primary *N*-nitramines **177** and **178**, which includes the nitration of *N*-alkyl carbamates **173**/**174** or *N*,*N*′-dialkyloxamides **170c** with N_2O_5 in TFE and the treatment of the resulting nitro compounds **175**, **176** and **172c** with liquid ammonia, without isolation, in the same solvent (Scheme 58). The method is safe and environmentally friendly. It affords ammonium nitrate, ethyl carbamate or oxamide as by-products, which can be used in agriculture as nitrogen fertilizers. In this method, the solvent (TFE) is easily recompressed (like in refrigerators) and returned to the process.

The above-considered environmentally friendly methods of nitration using dinitrogen pentoxide and alternative reaction media may serve in the near future as the basis for creating industrial processes, safe for personnel and the environment, for the production of energetic compounds and materials for military and civilian applications (mining industry, medicine and so on).

3. Nitro compounds as versatile reagents for organic synthesis

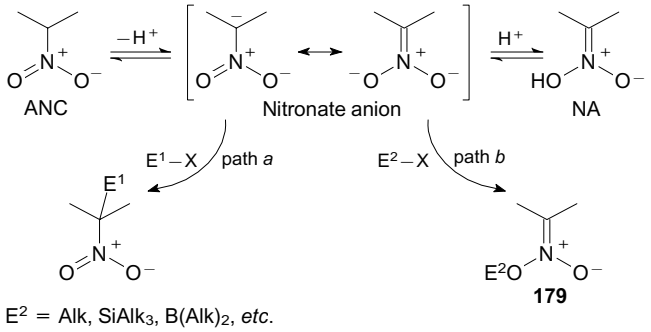
Nitro compounds are of applied interest as key components of EMs and active pharmaceutical ingredients (nitroglycerin, furacilin, isosorbide dinitrate, *etc.*).[209, 210] They are precursors for the preparation of many other commercially important compounds (dyes, polymers and so on). Besides, due to availability, stability and diverse reactivity, nitro compounds are among the most versatile and commonly used reagents in organic chemistry.[211 – 213] They are easily modified at the α-carbon atom and can be functionalized, in particular, by introducing amino or carbonyl groups. The Henry reaction,[12, 214] Nef reaction,[11] nitro-Michael reaction,[13, 215] nitro-Mannich reaction [216] and some other transformations of nitro compounds are well-known and widely used tools of modern organic synthesis. Russian researchers have made a significant contribution to the development of these methods in the second part of the 20th century.[6]

The further development of chemistry of nitro compounds in the 21st century arose from the following circumstances. First, conventional reactions of nitro compounds proved to be compatible with modern methods of asymmetric metal catalysis and organocatalysis, which offers new possibilities for the use of nitro compounds in the synthesis of enantiomerically pure biologically active molecules.[19, 217] On the other hand, new knowledge on the reactivity of nitronic acid derivatives resulted in the development of original approaches to the modification of the carbon skeleton of aliphatic nitro compounds.[218] Finally, the chemical utilization of expired basic energetic compounds, in particular TNT, is a challenging problem. Towards this direction, extensive research efforts are underway to discover new pathways of useful chemical transformations of these large-scale commercial products.

3.1. Nitroalkanes and nitronates: new approaches to selective functionalization of the carbon skeleton

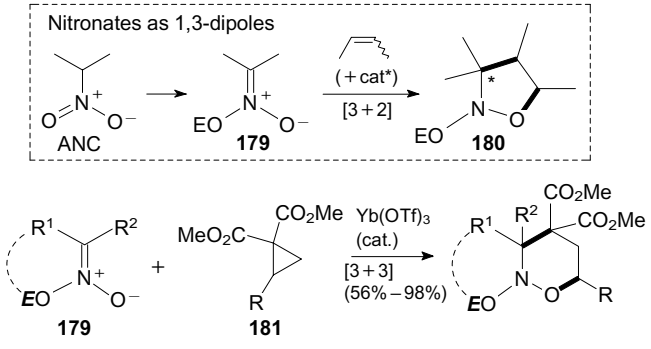
Conventional transformations of aliphatic nitro compounds (ANCs) are related to reactions of their conjugated bases (nitronate anions) serving as *C*-nucleophiles. The reactions of the latter with electrophiles allow the introduction of various substituents E^1 at the α-carbon atom of ANCs (Scheme 59, path *a*). On the other hand, ANCs can exist in equilibrium with their tautomers, nitronic acids (NAs). Although the nitro form is usually more stable than the *aci* form, the latter can be stabilized as *O*-esters, so-called nitronates **179** (path *b*).[219]

Scheme 59

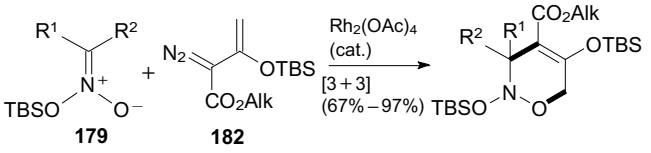


The structures of esters **179** greatly differ from the structures of parent ANCs, resulting in a significant difference in their reactivity and, as a consequence, in the extension of the range of available procedures for the functionalization of nitro compounds.[220] Nitronates **179**, as 1,3-dipoles, are involved in [3 + 2]-cycloaddition reactions with alkenes giving isoxazolines **180** (Scheme 60).[16] These reactions can be performed with high enantioselectivity in the presence of copper-based catalysts with bisoxazoline- and oxaazaborolidine-type chiral ligands.[221, 222]

Scheme 60



R = Ar, CH=CHPh; R^1, R^2 = H, Alk, Alk_{FG}; ***E*** = C, Si

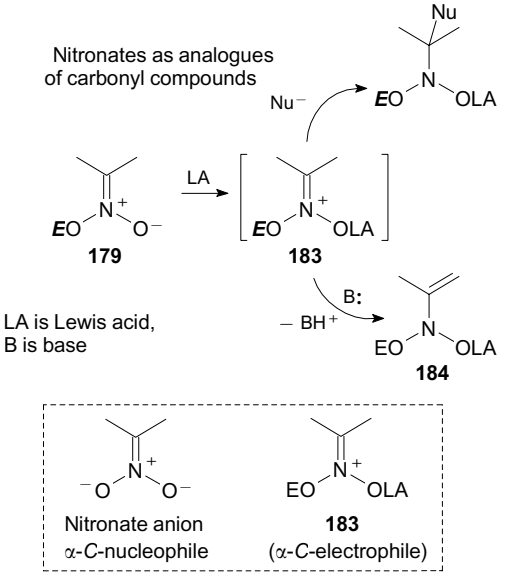


R^1, R^2 = H, Alk, Alk_{FG}; TBS = $SiMe_2Bu^t$

The range of [3+2]-cycloaddition reactions to nitronates **179** has recently been extended by the development of metal-catalyzed formal [3+3]-cycloaddition reactions involving donor-acceptor cyclopropanes **181**[223, 224] and enol diazoacetates **182**.[225] These transformations lead to profound modification of the nitro moiety by including it in the oxazine ring.

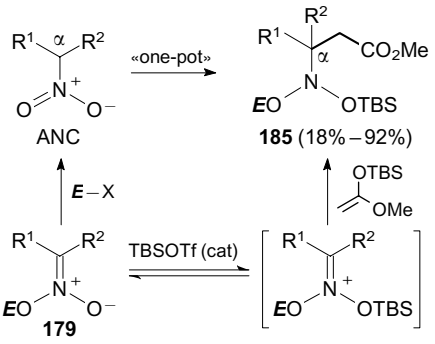
Nitronates **179** containing the C=N double bond can also be considered as analogues of carbonyl compounds and azomethines in terms of both *C*-electrophilic properties and reactions involving the α-CH position (Scheme 61). These transformations are activated by Lewis acids (LAs), which are coordinated to the oxygen atom of the nitronate moiety giving *N*,*N*-bis(oxy)iminium cations **183**.[220, 226] The latter can add nucleophiles or undergo deprotonation to form enamines **184**. It should be noted that cations **183** have an inverted polarity compared to nitronate anions.[227] In enamines **184**, the β-carbon atom, which is inert in the nitro compounds, can be involved in addition reactions.

Scheme 61



The concept of nitronates as analogues of carbonyl compounds was proposed in the ZIOC RAS in the early 2000s,[228] and its development in recent years led to the design of new efficient methods for the functionalization of α and β positions in ANCs and nitronates. Silicon derivatives proved to be the most efficient Lewis acids in this process. The use of these derivatives makes it possible to generate cations **183** from nitronates **179** and perform their transformations under relatively mild conditions.[229] These reactions significantly increase the scope for modifications of the carbon skeleton of nitro compounds. The general approach to the introduction of nucleophiles at the α position of nitroalkanes includes the transformation of ANC into nitronate **179** using a base and an electrophilic reagent and the trimethylsilyl triflate-catalyzed reaction of **179** with a nucleophile (*e.g.*, silyl ketene acetal) giving adduct **185** (Scheme 62). In the reaction product, the nucleophilic moiety is bound to the α-carbon atom of the starting ANC. The generation of nitronate **179** and the addition of a nucleophile can be steps of a single one-pot process.[227]

Scheme 62



R^1, R^2 = H, Alk, Bn, ***E*** = Et, TBS; Tf is triflate

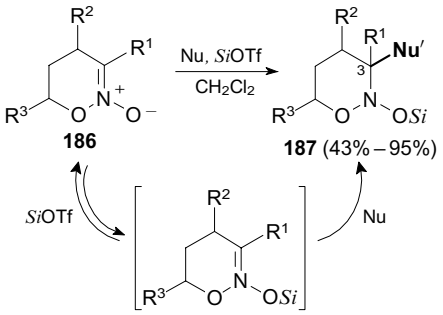
This procedure is applicable to different types of nitronates, including cyclic *O*-alkyl esters of nitronic acids **186**. Under these conditions, the latter compounds react with a wide range of *C*- and *N*-nucleophiles giving nitroso acetals **187** (Scheme 63).[230, 231] The new stereogenic centre C(3) in products **187** is usually formed stereoselectively.

Nitronates **186** are easily generated by not only the cyclization of appropriate δ-halogen-substituted nitroalkanes **188**[232] but also the [4+2]-cycloaddition reaction of nitroalkenes **189** with electron-donating olefins developed by Denmark and Thorarensen[233] (Scheme 64).

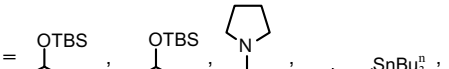
The coupling of some nucleophiles with nitronates **186** does not require strong Lewis acids. This was recently demonstrated by performing the successful addition of the cyanide anion in the presence of magnesium perchlorate (Scheme 65).[234] In this case, the cyclic structure of nitroso acetal is not preserved and the reaction affords cyanooximes **190** as the final products.

The functionalization of the β-carbon atom of ANCs is generally associated with the transformation of the latter into *N*,*N*-bis(oxy)enamines **184** (see Scheme 61). Enamines **184** exhibit dual reactivity and react with both electrophiles and nucleophiles at the β-C atom (Scheme 66). In the former case, these compounds behave as typical enamines;

Scheme 63

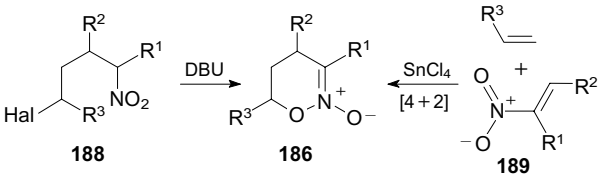


R^1 = H, Alk; R^2 = Ar, Alk, OBz; R^3 = Alk, OAlk;

Nu = 

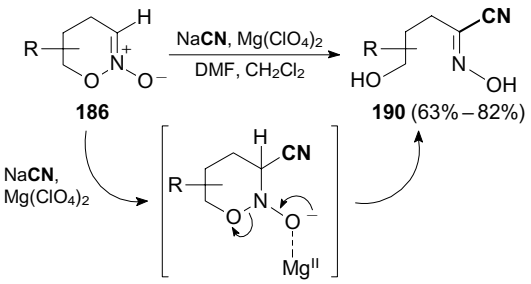
R_3SiCN, TBS – $NAlk_2$; *Si* = TMS, TBS

Scheme 64

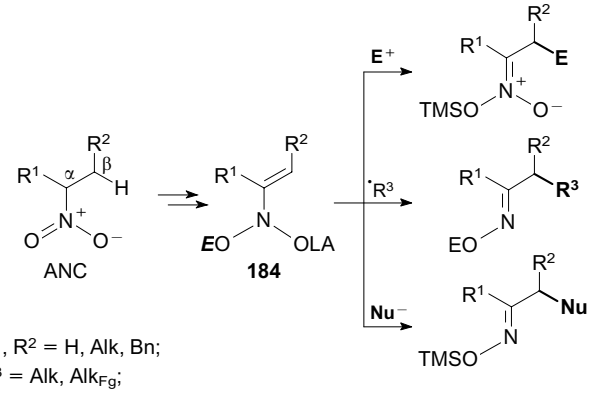


R^1 = H, Alk; R^2 = Ar, Alk, OBz; R^3 = Alk, OAlk;
DBU is 1,8-diazabicyclo[5.4.0]undec-7-ene

Scheme 65



Scheme 66

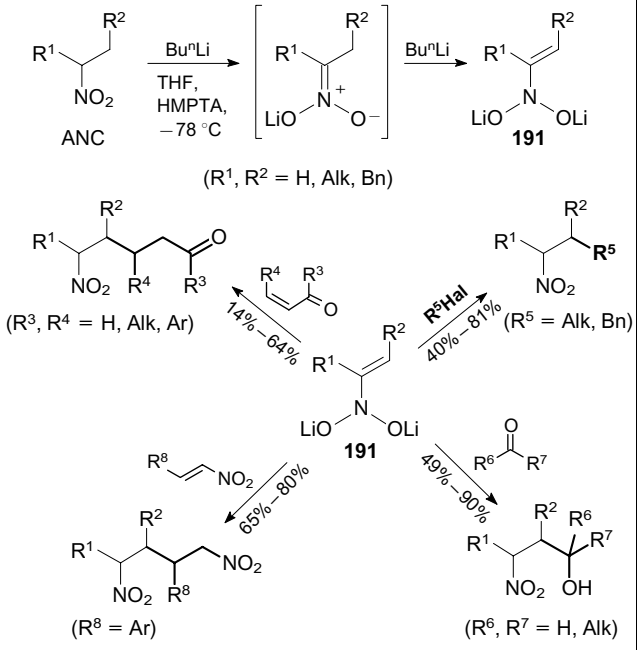


R^1, R^2 = H, Alk, Bn;
R^3 = Alk, Alk_{Fg};
Alk_{Fg} is alkyl group bearing a functionality

in the latter case, as nitroso acetals, the reactions of which are accompanied by the heterolytic cleavage of the weak nitrogen – oxygen bond.[235] Besides, free radicals $R^{3\bullet}$ can also be added at the C=C double bond in *N*,*N*-bis(oxy)enamines **184** followed by homolytic N – O bond cleavage.[236]

In the method proposed by Seebach and co-workers,[237] lithium *N*,*N*-bis(oxy)enamines **191** (so-called superenamines) are generated by the treatment of ANCs with excess butyllithium (Scheme 67). These compounds readily react (even at –78 °C) with such electrophiles as alkyl halides, carbonyl compounds and Michael acceptors to form the corresponding addition products.[238, 239]

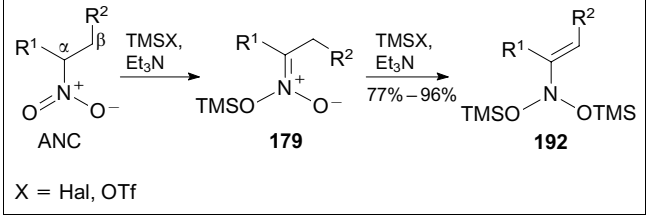
Scheme 67



HMPTA is hexamethylphosphoric triamide

However, the yields of functionalized nitro compounds are usually low because of high reactivity of superenamines **191**. Besides, this procedure does not tolerate many functional groups in ANCs. Stable bis-silyl ene nitroso acetals **192**, which are prepared by the double silylation of ANCs (Scheme 68),[240, 241] are more convenient synthetic equivalents of *N*,*N*-bis(oxy)enamines **184**.

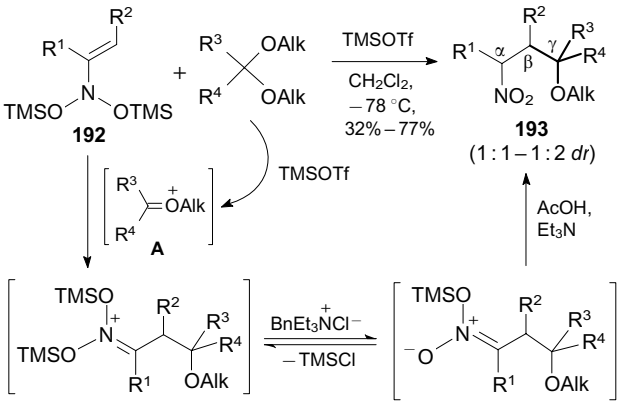
Scheme 68



X = Hal, OTf

The nucleophilicity of ene nitroso acetals **192** in the Mayr scale is much lower than that of typical enamines and is comparable with that of silyl enolates and allylsilanes.[242] The reaction with carboxonium cations **A** resulting in the formation of a new carbon – carbon bond (Scheme 69)[243] is an example of the successful electrophilic addition to *N*,*N*-

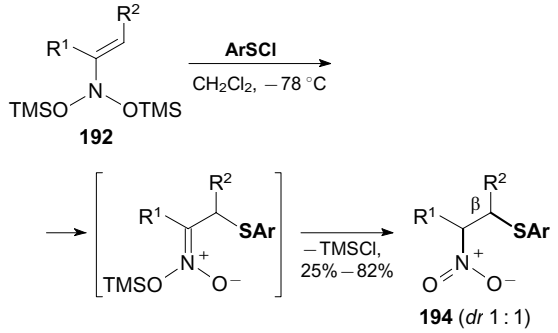
Scheme 69



bis(oxy)enamines **192**. Under the reaction conditions, the cations **A** are generated from the corresponding acetals and ketals under the action of trimethylsilyl triflate. The addition of these C-electrophiles at the C=C double bond affords γ-functionalized nitro compounds **193**.

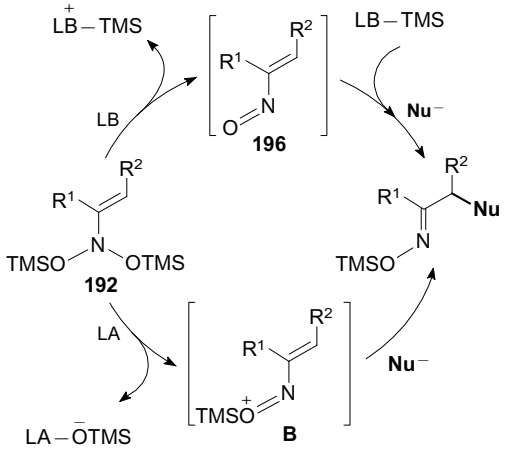
The reaction of *N*,*N*-bis(oxy)enamines **192** with sulfenyl halides gives diastereomeric β-thio-substituted nitro compounds **194** [Scheme 70, Eqn (1)].[244] Meanwhile, the halogenation of ene nitroso acetals **192** in the presence of tetrabutylammonium acetate produces nitroalkenes **189** *via* the elimination of halosilane from intermediate nitronates **195** [Scheme 70, Eqn (2)].[245]

Scheme 70



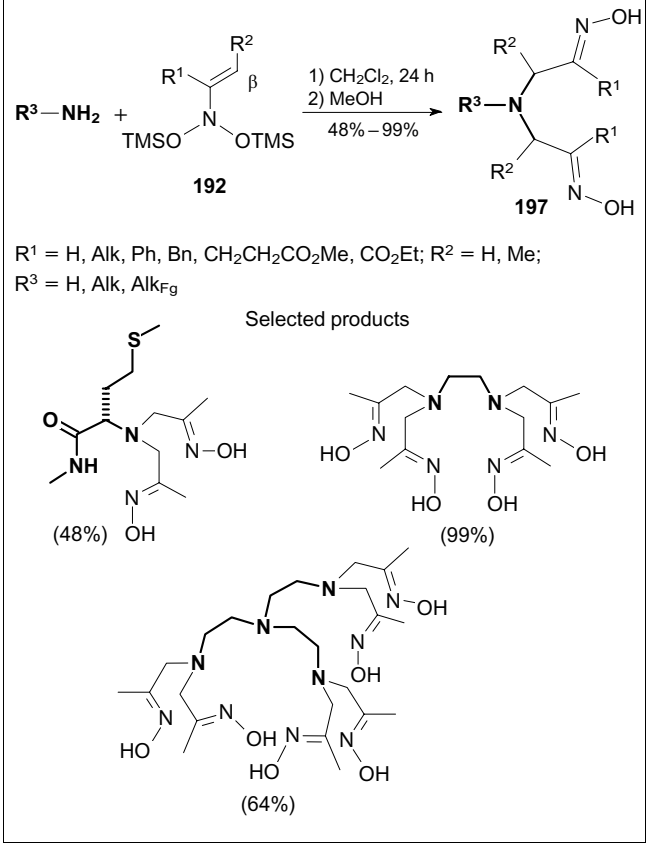
The nitrogen – oxygen bond in ene nitroso acetals **192** is weak due to $\pi \rightarrow \sigma^*_{N-O}$ and $n_O \rightarrow \sigma^*_{N-O}$ hyperconjugation and is prone to heterolytic cleavage.[246] Hence, compounds **192** can serve as a source of conjugated nitroso alkenes **196** or *N*-vinyl,*N*-oxynitrenium ions **B** (strong Michael acceptors), making it possible to introduce nucleophiles at the β position of the former ANC (Scheme 71). The generation of nitroso alkenes **196** from **192** is promoted by Lewis bases; the generation of *N*-vinyl,*N*-oxynitrenium ions **B**, by Lewis acids (through the coordination of LA to the oxygen atom of the N – O bond). The use of a particular activation method depends on the nature of the nucleophile. Weak nucleofuges are better activated by Lewis bases, while stronger ones by Lewis acids.

Scheme 71

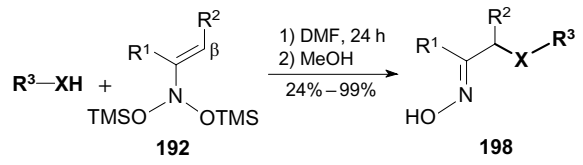


Amines belong to the first type of nucleophiles. Primary amines and ammonia selectively react with two molecules of ene nitroso acetal **192** in the absence of Lewis bases, the role of which is played by the amine itself (Scheme 72). This is one of the most commonly used methods for the synthesis of

Scheme 72

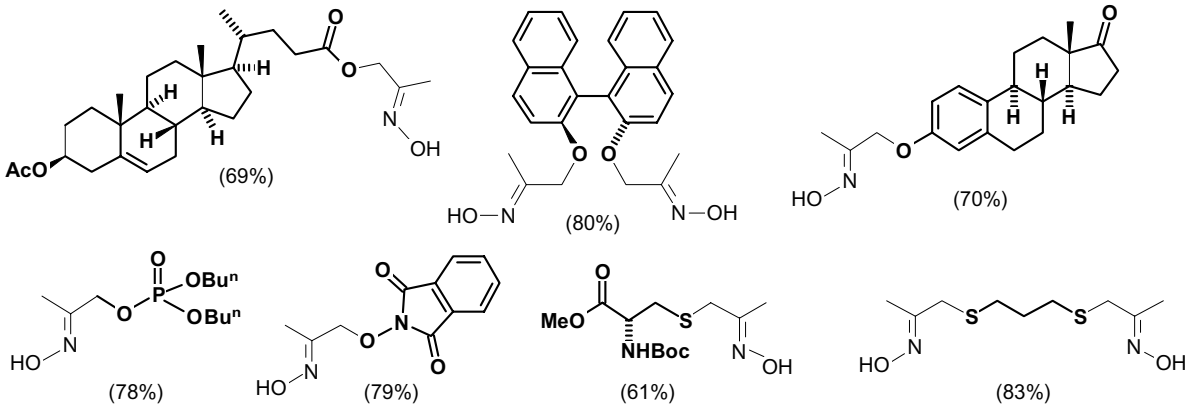


Scheme 73

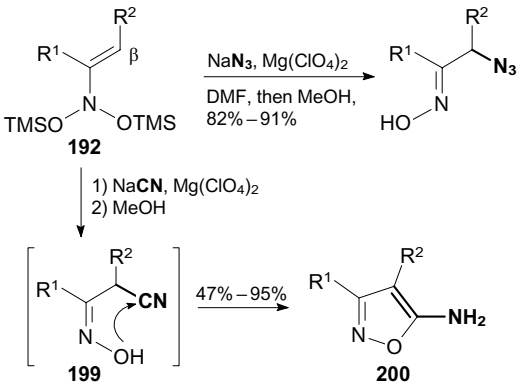


R^1 = H, Alk, Ph, Bn, $CH_2CH_2CO_2Me$, CO_2Et;
R^2 = H, Me;
R^3 = AlkC(O), ArC(O), Ac, *etc.* (X = O);
Alk, Ar, Ar_{Het}, Alk_{Fg} (X = S)

Selected products

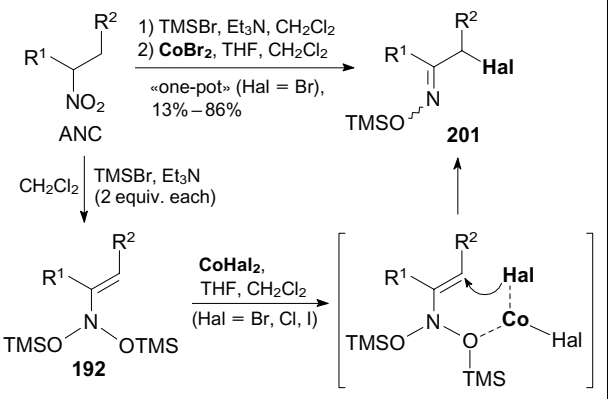


Scheme 74



R^1 = H, Alk, Ph, Bn, $CH_2CH_2CO_2Me$; R^2 = H, Me

Scheme 75



R^1 = H, Alk, Ph, Bn, $CH_2CH_2CO_2Me$; R^2 = H, Me

bis-α-amino oximes **197** from various amines and polyamines.[247]

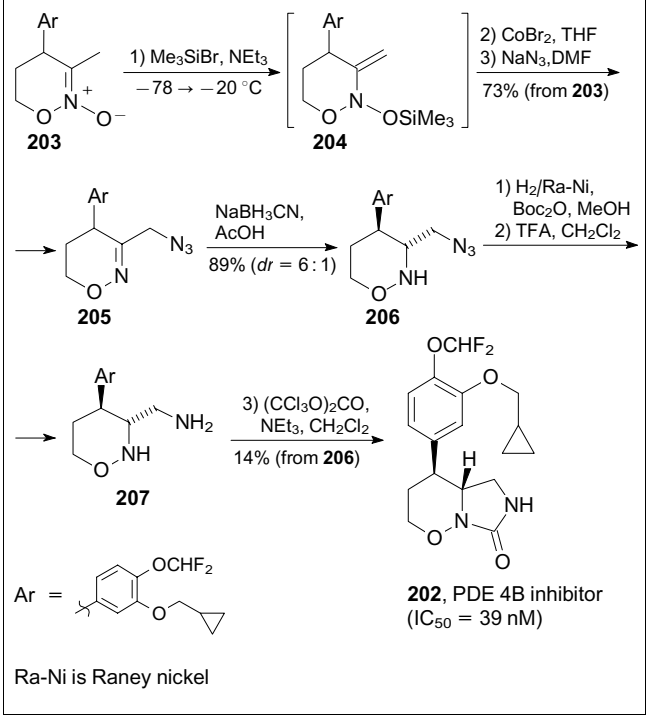
Another approach to the generation of conjugated nitroso alkenes **196** from ene nitroso acetals **192** under mild conditions is based on the treatment with dimethylformamide (a weak Lewis base). Different *O*- and *S*-nucleophiles (carboxylic acids, phenols, hydroxamic acids and thiols) react in DMF with enamines **192** to form, after desilylation, the corresponding α-oxy- or α-thio-substituted oximes **198** (Scheme 73).[246,248] In these reactions, nucleophiles are used in the available H form without the addition of reagents for their deprotonation.

Nucleophiles, which are not convenient to handle in the H form (*e.g.*, cyanide and azide anions), can be introduced in the reaction with enamines **192** as the corresponding silyl derivatives[249] or the *in situ* generated magnesium salts (Scheme 74).[250] The final products of the addition of the cyanide anion are 5-aminoisoxazoles **200**, which are formed through the cyclization of intermediate α-cyanoximes **199**.[234]

The use of *d*-metal salts, in particular cobalt salts, made it possible to perform the reactions of ene nitroso acetals **192** with such nucleophiles as halide and nitrate ions, which do not directly add to nitroso alkenes.[251,252] The *d*-metal cation is apparently coordinated by the oxygen atom, thereby facilitating the heterolytic cleavage of the nitrogen – oxygen bond in **192** (Scheme 75). It is worth noting that silyl ethers of α-halogen-substituted oximes **201** can be synthesized from ANCs in a one-pot fashion by the successive addition of a silylating agent (to generate enamines **192**) and cobalt halide.

The proposed methods for the functionalization of nitronates are suitable for the preparation of biologically active substances, in particular oxazinoimidazolidinone **202**, a potent phosphodiesterase 4B inhibitor (Scheme 76).[253] The silylation of cyclic nitronate **203** gave *N*,*N*-bis(oxy)enamine **204**. The subsequent Co^{II} -promoted addition of a bromide anion at the C=C double bond and the replacement of bromine with the azide anion resulted in the formation of azido derivative **205**. The hydride reduction of the C=N double bond and the hydrogenolysis of the azido group in intermediate **206** gave aminomethyl-

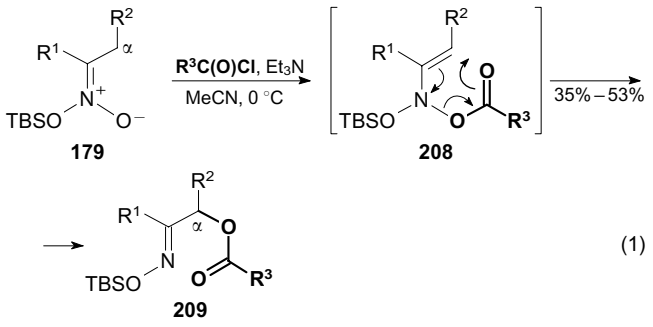
Scheme 76



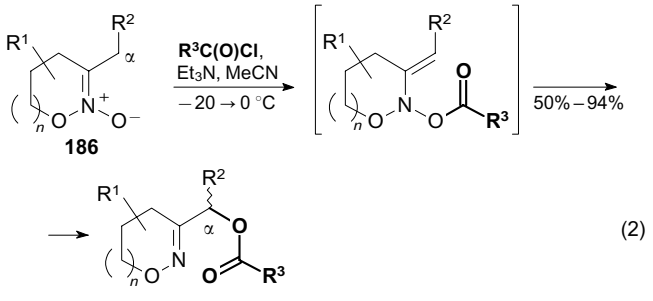
substituted 1,2-oxazine **207**, which was transformed into target product **202** by the treatment with triphosgene.

The α position in nitronates can be functionalized not only by silylation but also using other electrophilic reagents. Recently, a method was developed for the oxygenation of silyl nitronates **179** with acyl chlorides.[254] In the first step, the reaction affords *N*-acyloxy enamines **208**, which are transformed into α-acyloxy oxime esters **209** [Scheme 77, Eqn (1)]. The [3,3]-sigmatropic rearrangement is driven by

Scheme 77



R^1 = Me, Ph; R^2 = H; R^3 = Bu^t, Ar

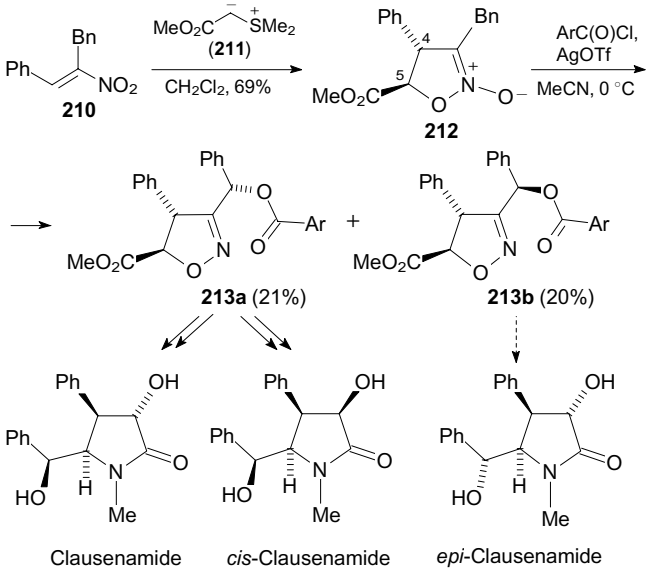


R^1 = H, Alk, Ar, OAlk, OBz; R^2 = H, Me; R^3 = Bu^t, Pr^i, Ar; *n* = 0, 1

the cleavage of the weak N – O bond and the formation of a stronger C – O bond. A similar tandem acylation/rearrangement reaction is applicable to the functionalization of cyclic nitronic *O*-esters **186** [Eqn (2)].

The oxygenation of the α position in nitronates *via* the acylation proved to be applicable for the preparation of precursors of clausenamide alkaloids (Scheme 78).[254] The key intermediate, isoxazoline *N*-oxide **212**, was prepared by the stereoselective [4 + 1]-cycloaddition of nitroalkene **210** (available from 2-phenylnitroethane) to ylide **211**. The acylation of **212** with *para*-nitrobenzoyl chloride afforded a mixture of diastereomeric isoxazolines **213a** and **213b**. The latter compounds are precursors for the preparation of clausenamide, *cis*-clausenamide and *epi*-clausenamide by known procedures.[255]

Scheme 78



Ar = 4-$NO_2C_6H_4$

Therefore, progress in chemistry of nitronic esters achieved in the past two decades resulted in the creation of a wide range of tools for modification of aliphatic nitro compounds. The most important methods include the inversion of the polarity of nitroalkanes, new cycloannulation reactions of nitronates and methods for the functionalization of the α position in nitronates and the β position in nitro compounds. These methods proved to be efficient, as demonstrated by their successful application in the total synthesis of complex biologically active compounds and natural products.

3.2. Stereoselective reactions of nitroolefins in the synthesis of biologically active substances

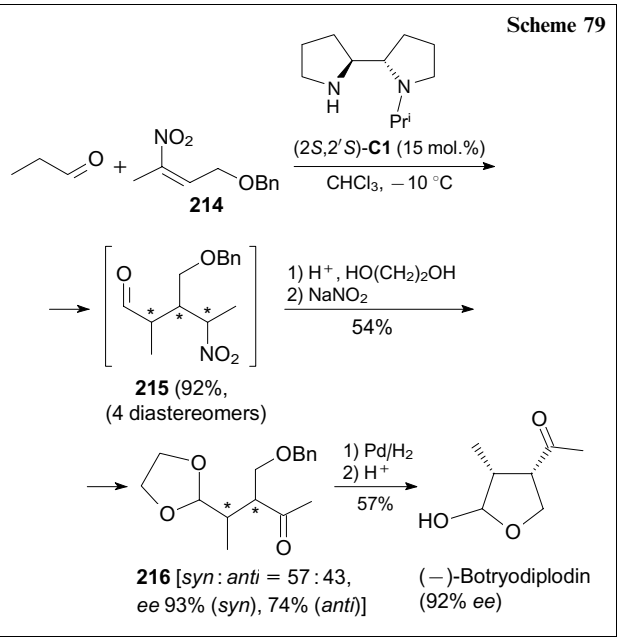
α-Nitroolefins comprise a class of ANCs very useful in organic synthesis. Due to availability (these compounds can easily be prepared by the condensation of nitroolefins with aldehydes) and high chemical reactivity, these compounds are used as precursors for the preparation of a wide range of nitrogen-containing compounds for different applications.[256 – 259] In particular, α-nitroolefins readily add different nucleophiles to form β- or γ-functionalized nitroolefins serving as precursors of many biologically active substances.[211] Below we consider only some most interesting asymmetric reactions of nitroalkenes with carbo- and

heteronucleophiles, which were applied to perform stereoselective synthesis of natural compounds and other biologically active substances evaluated in clinical or preclinical trials, in particular the synthesis of the most active enantiomers of pharmaceuticals (see also reviews [19, 260–262]). In these reaction, chiral catalysts or chiral auxiliaries of the substrates generally serve as stereoinducers. Catalytic reactions of nitroolefins are most promising for practical applications.

3.2.1. Asymmetric reactions of nitroolefins with aldehydes and ketones

Enolizable aldehydes and ketones containing a reactive site in the α position to the carbonyl group undergo enantioselective addition to nitroolefins in the presence of chiral secondary or primary amines, which activate the carbonyl compound by forming enamine intermediates.[263] Alexakis and co-workers [264, 265] found that the reaction of propanal with nitroalkene **214** catalyzed by the bis-pyrrolidine derivative (2*S*,2′*S*)-**C1** affords diastereomeric Michael adducts **215** (Scheme 79). The acetalization and Nef reactions produced ketone **216**, with the number of diastereomers decreasing to two. The catalytic hydrogenation and deprotection of *syn* isomer **216** (93% *ee*) gave the natural antibiotic (−)-botryodiplodin with a wide range of biological activity isolated from the rot fungus *Botryodiplodia theobromae*.[266–268]

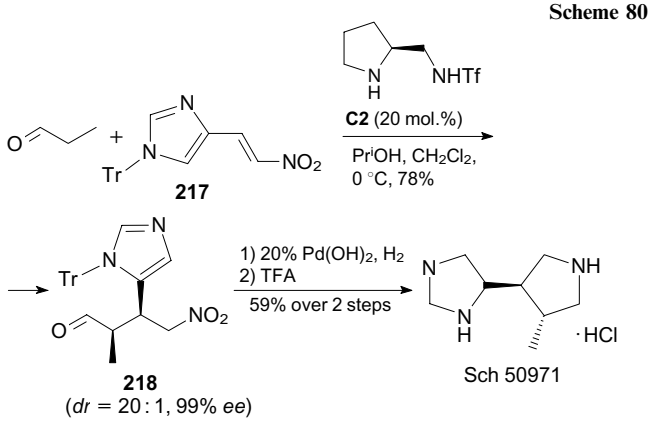
Scheme 79



Wang *et al.*[269] reported a similar synthesis of pyrrolidine derivatives, in particular the product Sch 50971. The latter is a potent histamine H3 receptor agonist, which was evaluated in clinical trials as an agent for the treatment of Alzheimer's disease.[270] The key step in this synthesis is the amine (*S*)-**C2**-catalyzed asymmetric addition of propanal to nitroolefin **217** giving adduct **218** with very high *syn*-diastereo- and enantioselectivity (Scheme 80). Compound **218** was transformed into the target product Sch 50971 by the reductive cyclization and deprotection of the imidazole ring.

The asymmetric synthesis of 3-substituted 4-nitrobutanal derivatives **220**, close precursors of γ-aminobutyric acid (GABA) analogues, was simultaneously accomplished by

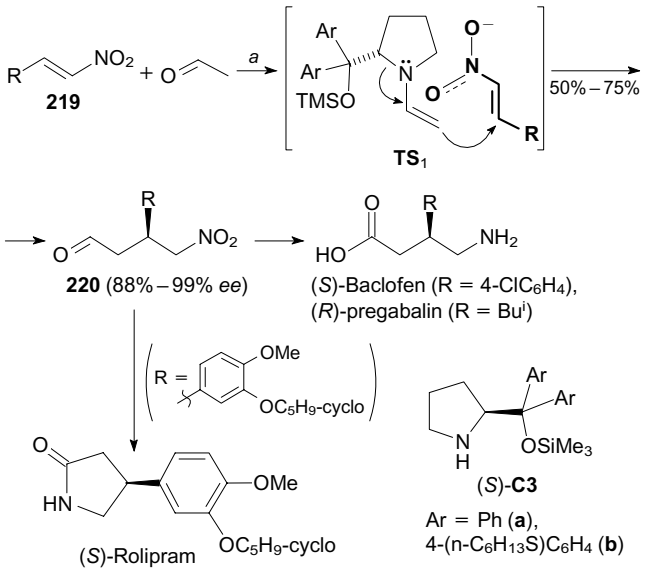
Scheme 80



Tr is trityl

two research teams headed by List [271] and Hayashi.[272] Adducts **220** were found to be enantioselectively produced from nitroolefins **219** and acetaldehyde in the presence of the silylprolinol derivative (*S*)-**C3a** (10 mol.% – 20 mol.%) (Scheme 81). The reaction proceeds through the formation of enamine in the transition state $\mathbf{TS_1}$. The oligomerization of acetaldehyde was suppressed by performing the reaction in polyethylene glycol PEG-400 in the presence of the catalyst (*S*)-**C3b** (10 mol.%) containing long-chain alkylthio groups and a benzoic acid additive.[273] Adducts **220** were transformed into the enantiomerically enriched drugs (*S*)-baclofen, (*S*)-rolipram and (*R*)-pregabalin by the oxidation and hydrogenation.[274–276]

Scheme 81



(*a*) (*S*)-**C3a** or (*S*)-**C3b**, BzOH (10 mol.% – 20 mol.%), MeCN, DMF, 1,4-dioxane, or PEG-400

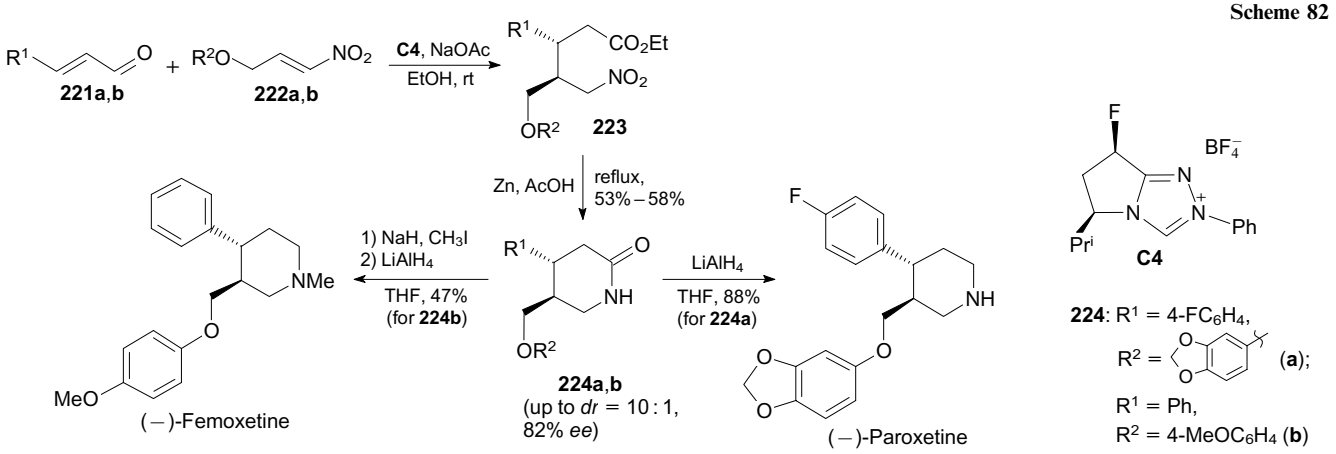
Rovis and co-workers [277] developed an efficient method for the stereoselective synthesis of δ-lactams based on the reaction of nitroalkenes with enals catalyzed by chiral heterocyclic carbenes. They applied this method to synthesize (−)-paroxetine, a serotonin reuptake inhibitor, and its analogue (−)-femoxetine. The homoenolate, which was

prepared by the treatment of α,β-enals **221** with the **C4** – NaOAc system, underwent stereoselective addition to functionalized nitroalkenes **222** to give δ-nitro esters **223** (Scheme 82). The latter were transformed *in situ* into δ-lactams **224** by the reduction of the nitro group (Zn – AcOH) and lactamization. The final steps of the synthetic sequence were the *N*-methylation (in the case of **224b**) and reduction of the amide group ($LiAlH_4$).

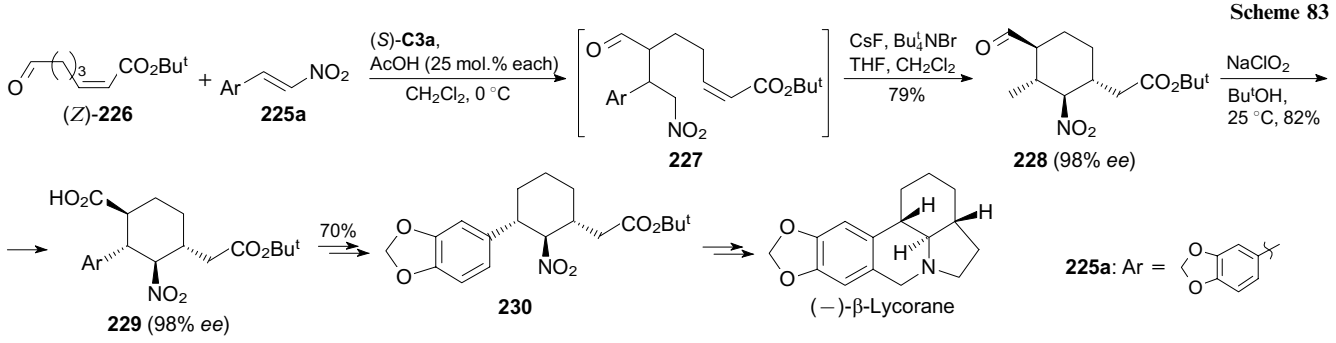
Hong *et al.*[278] accomplished the enantioselective synthesis of the tetracyclic alkaloid (−)-β-lycorane from nitrostyrene derivative **225a** and α,β-unsaturated aldehydoester (*Z*)-**226**. Such alkaloids (*Amaryllidaceae*) exhibit anticancer activity and are analogues of galantamine used for the treatment of Alzheimer's disease.[279, 280] Adduct **227**, which was produced in the presence of the prolinol catalyst (*S*)-**C3a**, was converted *in situ* into cyclohexane derivative **228** (single diastereomer, 98% *ee*) by the treatment with a base (CsF) under phase-transfer catalysis conditions (Bu^n_4NBr) (Scheme 83). The oxidation of aldehyde **228** to acid **229** and the subsequent decarboxylation of the latter gave product **230**, a close precursor of (−)-β-lycorane. A similar reaction sequence using aldehydoester (*E*)-**226** afforded isomeric α-lycorane.

Zhao and co-workers[281] simplified the synthesis of α- and β-lycoranes by catalyzing the reaction simultaneously with pseudoisomeric derivatives of quinine **C5** or quinidine **C6** bearing a thiourea group and (*S*)-proline. In this pair, proline enantioselectively catalyzes the asymmetric Michael reaction between (*E*)-**226′** and nitroolefin **225a** (enamine catalysis), while the alkaloid co-catalyst provides

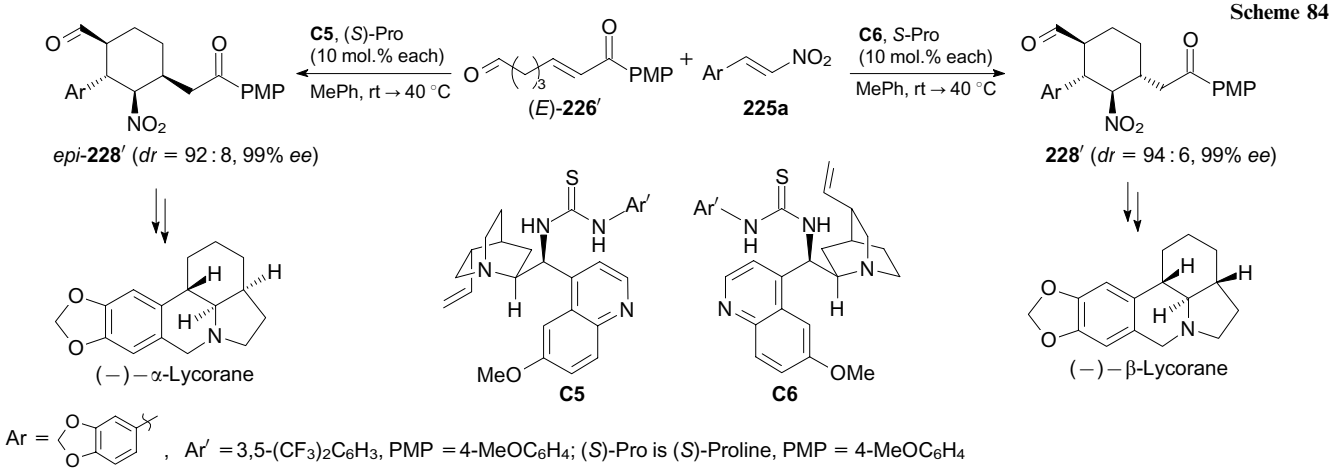
Scheme 82



Scheme 83



Scheme 84



Ar = , Ar′ = 3,5-$(CF_3)_2C_6H_3$, PMP = 4-$MeOC_6H_4$; (*S*)-Pro is (*S*)-Proline, PMP = 4-$MeOC_6H_4$

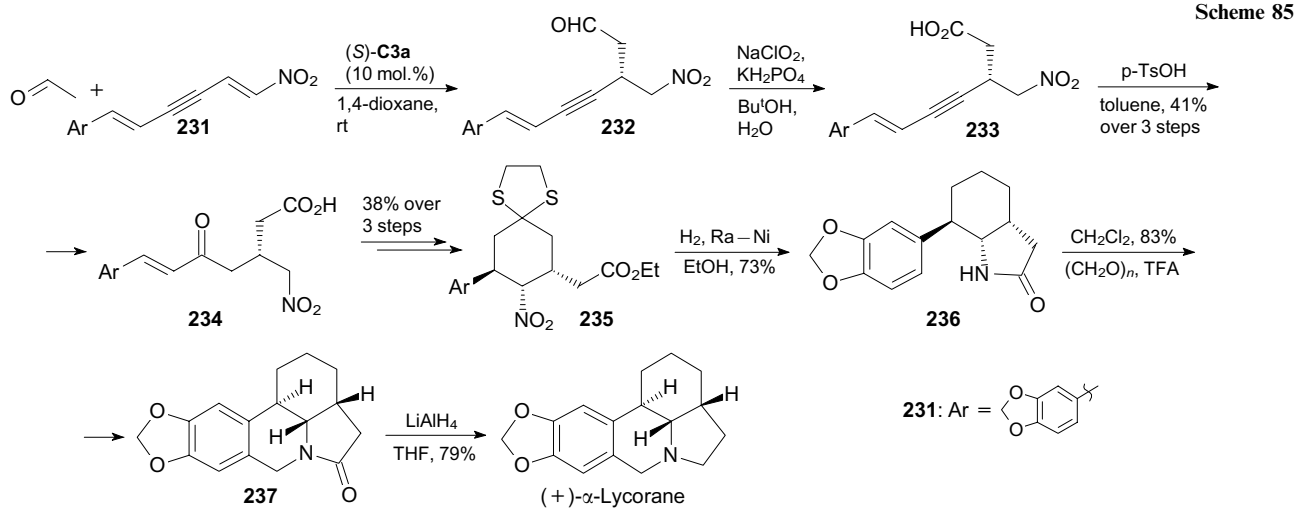
the stereocontrol of cyclization by forming hydrogen bonds with the reagent (Scheme 84). This approach enabled the stereoselective synthesis of precursors **228′** and *epi*-**228′** and their transformation to the target alkaloids according to a scheme analogous to that described above.

Shao and co-workers[282] developed an alternative asymmetric synthesis of (+)-α-lycorane based on the addition of acetaldehyde to nitrodienyne **231** in the presence of (*S*)-**C3a** (10 mol.%). The resulting 1,2-adduct **232** was oxidized *in situ* to γ-nitro acid **233**. The hydrolysis of the alkyne group in **233** gave acid **234** containing the α,β-enone moiety (Scheme 85). The transformation of compound **234** into nitrocyclohexane **235** (Ref. 283) and the Raney nickel-promoted cascade reaction sequence of compound **235** (deprotection, hydrogenation and lactamization) afforded bicyclic lactam **236**. The subsequent cyclization and reduction of lactam **237** ($LiAlH_4$) completed the synthesis of (+)-α-lycorane.

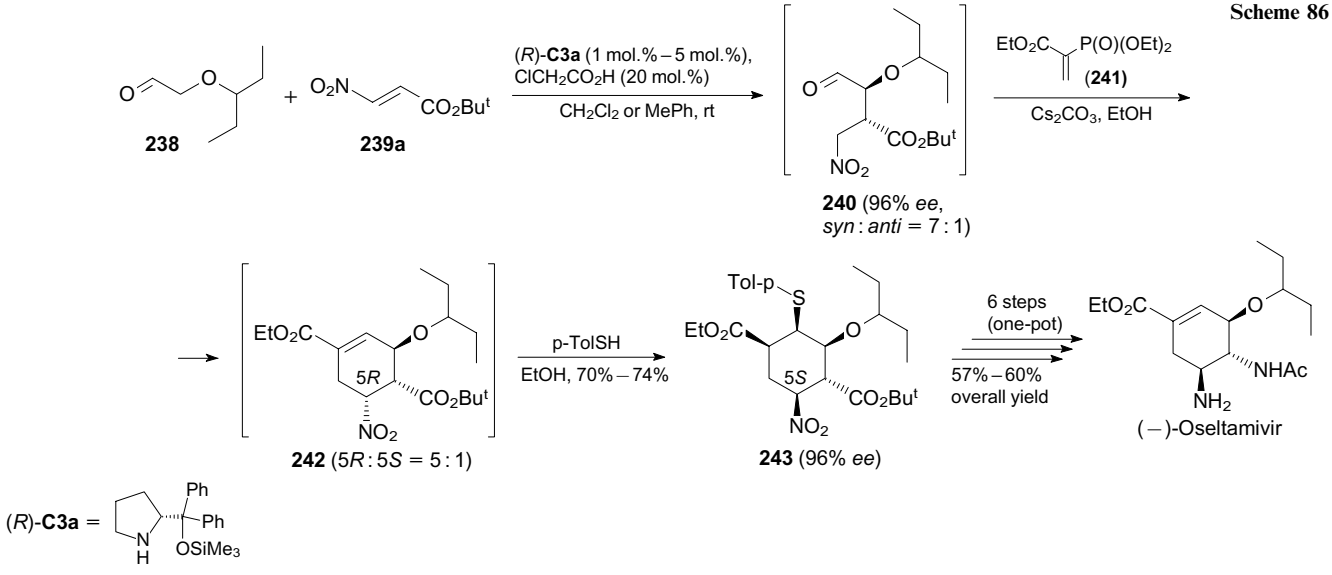
Hayashi and co-workers[284,285] reported the enantioselective synthesis of oseltamivir, a neuraminidase inhibitor against avian influenza, in particular against the strain H5N1 (Scheme 86).[286] The key step was the prolinol (*R*)-**C3a**-catalyzed asymmetric addition of glycolaldehyde ether **238** to β-nitroacrylate **239a** giving nitro aldehyde **240** with high diastereo- and enantioselectivity. The treatment of compound **240** with vinylphosphonate **241** in the presence of a base (Cs_2CO_3) triggered the Michael and Horner – Wadsworth – Emmons (HWE) domino reaction sequence giving cyclohexene derivative **242**. The thiolation of **242** was accompanied by epimerization. Product **243** having the required 5*S* configuration was transformed into (−)-oseltamivir in six steps by a one-pot procedure.

A more convenient (five steps, two synthetic operations) method for the synthesis of oseltamivir was proposed by Ma's research group.[287] They performed the reaction of glycolaldehyde ether **238** with *Z*-nitroenamine **244a** instead of β-nitroacrylate **239a** in the presence of prolinol ether (*S*)-**C3c** with the opposite configuration of the stereocentre as the catalyst (Scheme 87). This reaction directly produced the desired (2*R*,3*S*) isomer of adduct **245**. The Michael reaction between compounds **238** and **244a** can be performed in the presence of the more available catalyst (*S*)-**C3a** in combination with $ClCH_2CO_2H$,[288] *rac*-mandelic acid or 2,4-dinitrophenol[289] without loss of stereoselectivity. In this case, labile aldehyde **238** can be conveniently generated *in situ* from the appropriate diethyl acetal immediately before the reaction.[290] Compound **245** was transformed *in situ* into functionalized nitrocyclohexene **246** and

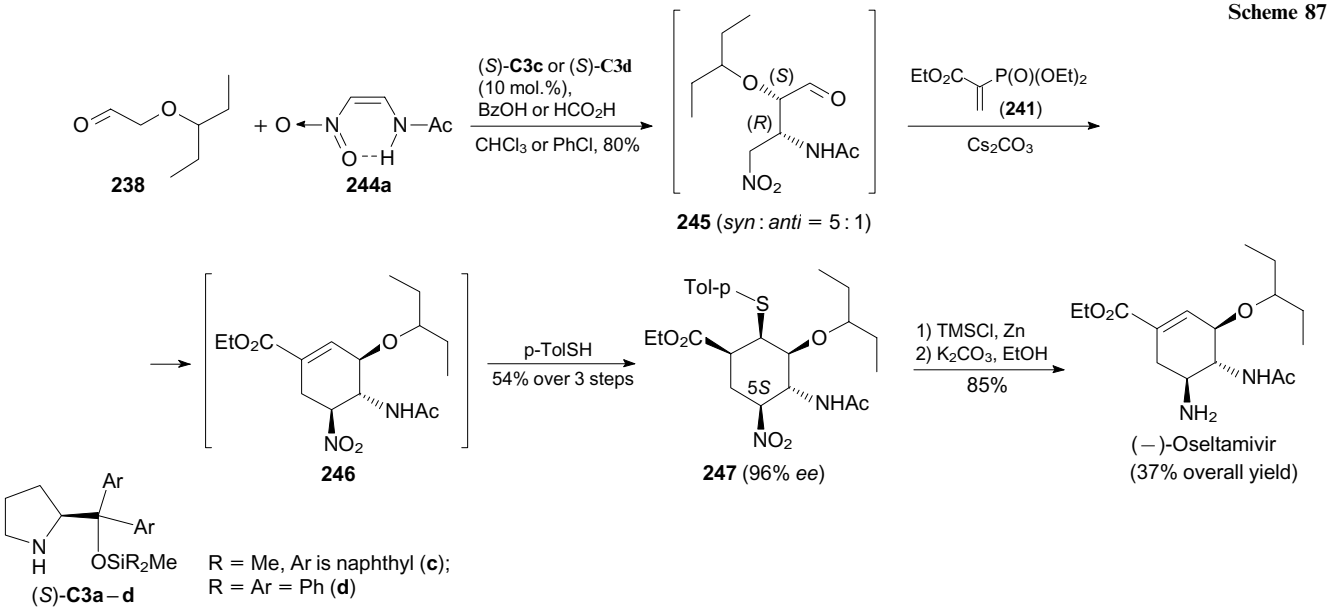
Scheme 85



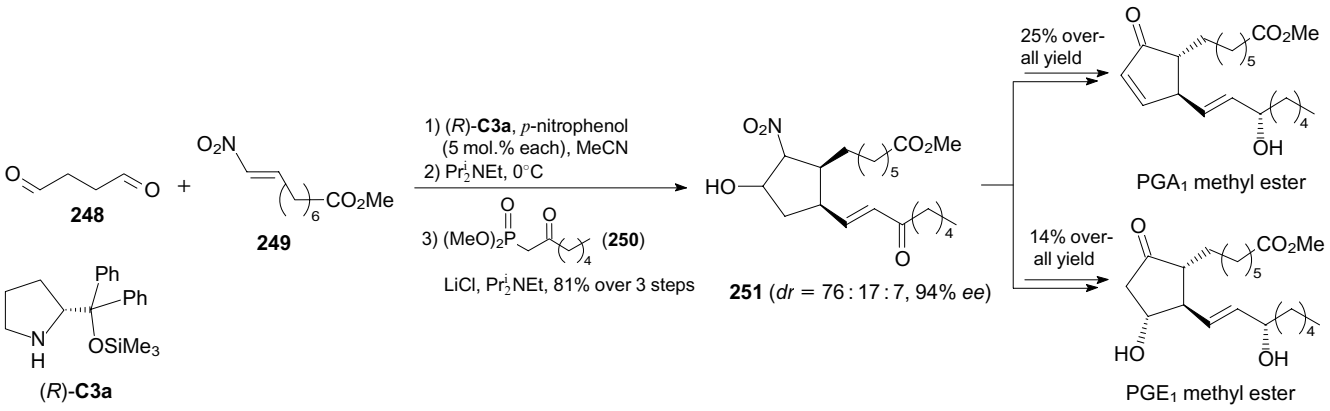
Scheme 86



Scheme 87



Scheme 88



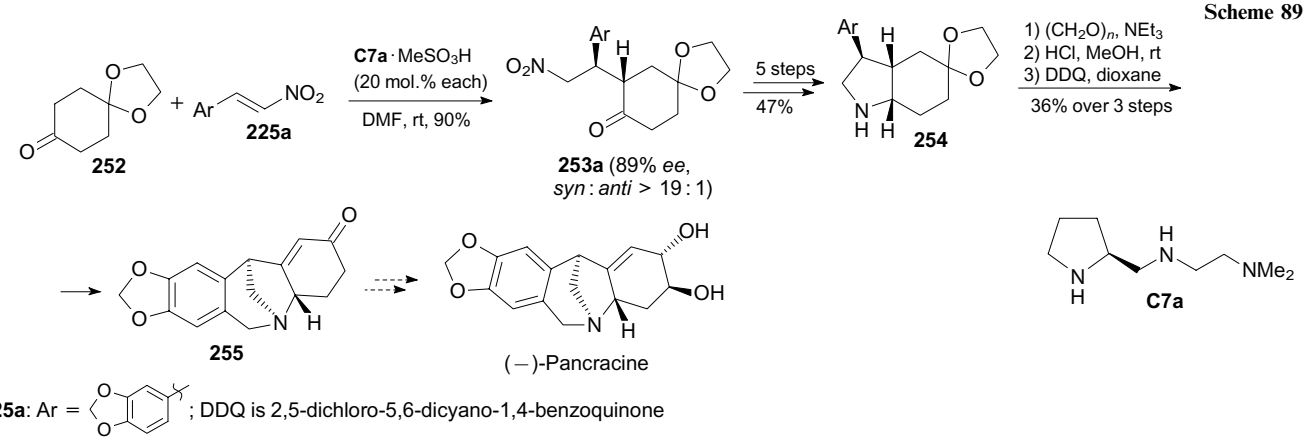
then into nitrocyclohexane derivative **247** by a Hayashi's method [284] in an overall yield of 54% with 96% *ee*. The total synthesis of oseltamivir was completed by the reduction of the nitro group (Zn/TMSCl) and elimination of the arylthio group (K_2CO_3). Later, Hayashi and co-workers [285, 291] improved Ma's method using the (*S*)-**C3d** – HCO_2H – PhCl catalytic system. This made it possible to completely exclude the solvent evaporation/removal and isolation of intermediates. Authors believe that this efficient method (37% overall yield) may be applied in industrial.

Hayashi and Umemiya [292] applied functionalized nitroalkene **249** for the stereoselective synthesis of prostaglandins.[293] The tandem reaction sequence includes the silylprolinol (*R*)-**C3a**-catalyzed asymmetric addition of dialdehyde **248** to nitroalkene **249**, the stereoselective intramolecular cyclization of the resulting adduct (Henry reaction) and olefination (HWE) with β-keto phosphonate **250** (Scheme 88). The one-pot reaction gave key chiral intermediate **251** containing all carbon atoms of prostaglandins in 81% yield with 94% *ee* (for the major diastereomer) starting from three simple molecules (**248** – **250**). Subsequent transformations of functionalities in **251** and epimerization of the α-side chain afforded methyl ethers of prostaglandins E_1 and A_1 in an overall yield of 14% and 25%, respectively.

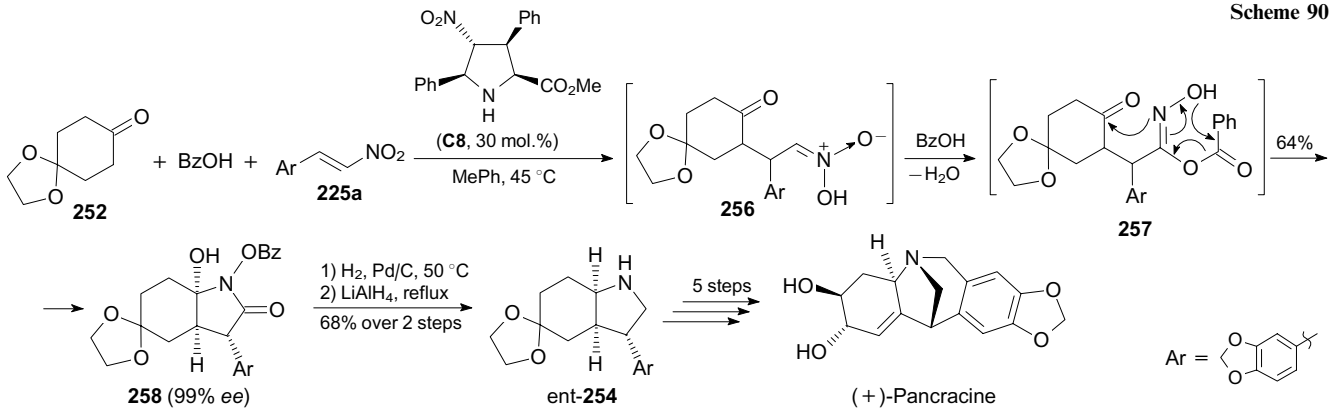
Ketones are less active nucleophiles than aldehydes. Hence, special polyfunctional catalysts are required for the asymmetric reactions of ketones with nitroalkenes to proceed. Pansare *et al.*[294] found that ketone **252** stereoselectively reacts with nitroolefin **225a** in the presence of pyrrolidine-containing triamine **C7a** to form nitroketone **253a** with 89% *ee* (Scheme 89). Adduct **253a** was transformed into *cis*-octahydroindole **254** *via* the reduction, cyclization, deprotection and hydrogenation. Compound **254** served as the precursor for the synthesis of polycyclic compound **255** with the (−)-pancracine skeleton (three steps, 36% overall yield), which was transformed into the target alkaloid by a known method.[295]

Recently, Cossío and co-workers [296] proposed an approach for the synthesis of enantiomeric (+)-pancracine, which differs from Pansare's method in that the asymmetric Michael reaction between compounds **225a** and **252** was catalyzed by proline derivative **C8** in the presence of BzOH (Scheme 90). Under these conditions, BzOH reacts with the *aci* form of primary Michael adduct **256** affording unstable intermediate **257**, which was stereoselectively (99% *ee*) rearranged to lactam **258** containing three chiral centres with the desired configuration. The subsequent hydrogenation and reduction of lactam **258** produced octahydroindole *ent*-**254**, a precursor of (+)-pancracine.

Scheme 89



Scheme 90



A method developed by Pansare *et al.*[294] provides a route to other useful indolizidine derivatives.[297] The triamine **C7a**-catalyzed reaction of 4-methoxy-β-nitrostyrene (**225b**) with ketone **252** gave nitro ketone **253b** with 92% *ee* (Scheme 91). The Baeyer – Villiger oxidation of **253b** afforded lactone **259**, which was converted to octanoate **260** *via* methanolysis and hydrolysis of ketal. The partial reduction of the nitro group in **260** with $Zn-NH_4Cl$ and triacetoxyborohydride gave hydroxylamine **261**. The latter was transformed into the alkaloids (+)-ipalbidine and (+)-antofine by the reductive pyrrolidine ring closure and subsequent transformations of compound **262**. (+)-Ipalbidine is used as an analgesic.[298] (+)-Antofine is an enantiomer of the natural compound with anticancer and antiviral activity.[299, 300]

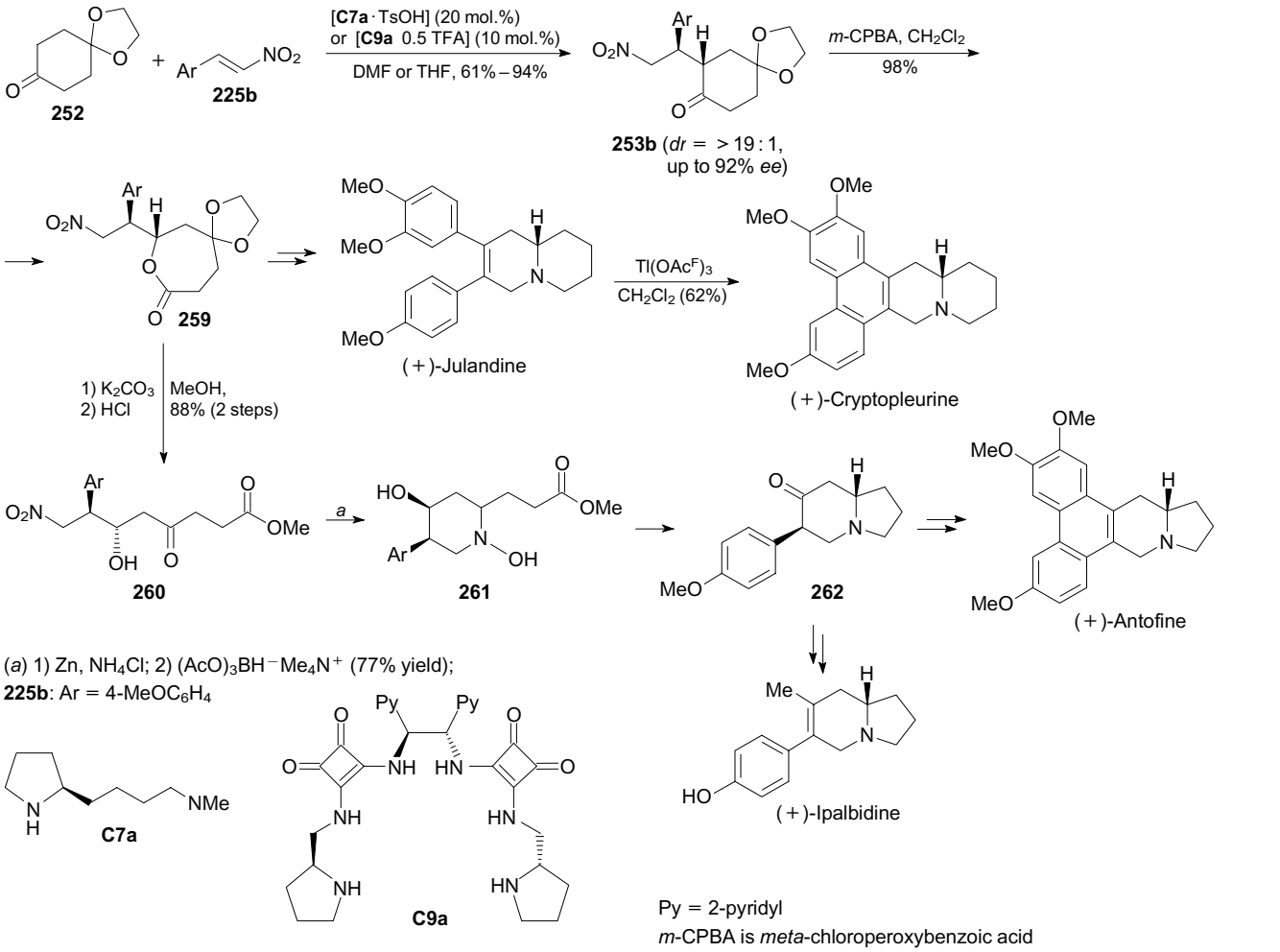
Nitroolefins proved to be useful for the stereoselective synthesis of quinolizidine alkaloids,[301] in particular, the antibiotics (+)-julandine[302] and (+)-cryptopleurine, the latter being an antipode of the compound with antiviral and anticancer activity.[303, 304] Recently, Zlotin and co-workers[305] showed that the Michael reaction between compounds **252** and **225b** is efficiently catalyzed by not only triamine **C7a** but also the C2-symmetric bis-pyrrolidine **C9a** modified with 3,4-diaminocyclobut-3-ene-1,2-dione (squaramide) moieties (see Scheme 91). This catalyst is also a good chiral inductor. Besides, due to poor solubility in organic solvents, it can be isolated from the reaction mixture as a salt with TFA and was reused in this reaction without loss of the rate and selectivity.

Chavan *et al.*[306] developed a method for the asymmetric synthesis of the antidepressant (−)-venlafaxine (EffexorXR®) based on the asymmetric addition of cyclohexanone to nitroolefin **225b** catalyzed by triamine **C7a** (20 mol.%). This synthesis gave nitro ketone **263** in 79% yield with 99% *ee* (Scheme 92). In this case, the yield of product **263** was increased to 92%, although with a certain loss of enantioselectivity (to 96% *ee*) by using the bis-pyrrolidine **C9a** – 0.5 (TFA) (10 mol.%) system instead of the catalyst **C7a**.[305] The stepwise reduction of carbonyl and nitro groups in compound **263** with $NaBH_4$ and the $NiCl_2 \cdot 6H_2O-NaBH_4$ system followed by the amidation gave Cbz-protected product **264**. The latter was converted to olefin **265** by mesylation and dehydration. The *N*-methylation and trivial transformations of amine **266** completed the total synthesis of (−)-venlafaxine in 22% yield with respect to nitroolefin **225b**.

Kokotos and co-workers[307] identified polyfunctional thioureas containing an α-amino acid moiety as a promising class of catalysts for reactions of nitroolefins with ketones. Compounds **C10** and *ent*-**C10** proved to be the catalysts of choice. In the presence of these catalysts, ketones **267** reacted with β-nitrostyrenes **225c,d** to form Michael adducts **268** in high yield with up to 99% *ee* (Scheme 93). This method was applied to synthesize the enantiomerically pure drugs (*S*)-phenibut and (*S*)- or (*R*)-baclofen with anxiolytic and spasmolytic activity by the Baeyer – Villiger oxidation of adducts **268** and known transformations of γ-nitro esters **269**.[308, 309]

Ma and co-workers[310] proposed a method for the synthesis of the neuraminidase inhibitors zanamivir, laninamivir and CS-8958 for the treatment of influenza.[311, 312] The key steps of the synthesis are the enantioselective addition of acetone to 2-(nitrovinyl)carbamate **244b** in the presence of aminothiourea (2*S*)-**C11** and the stereoselective Henry

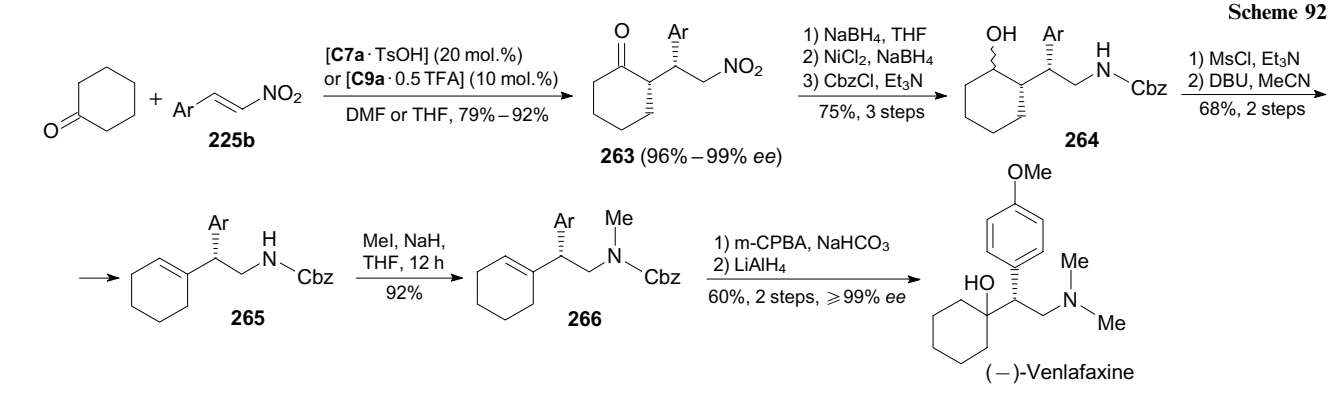
Scheme 91



(*a*) 1) Zn, NH_4Cl; 2) $(AcO)_3BH^-Me_4N^+$ (77% yield);
225b: Ar = 4-$MeOC_6H_4$

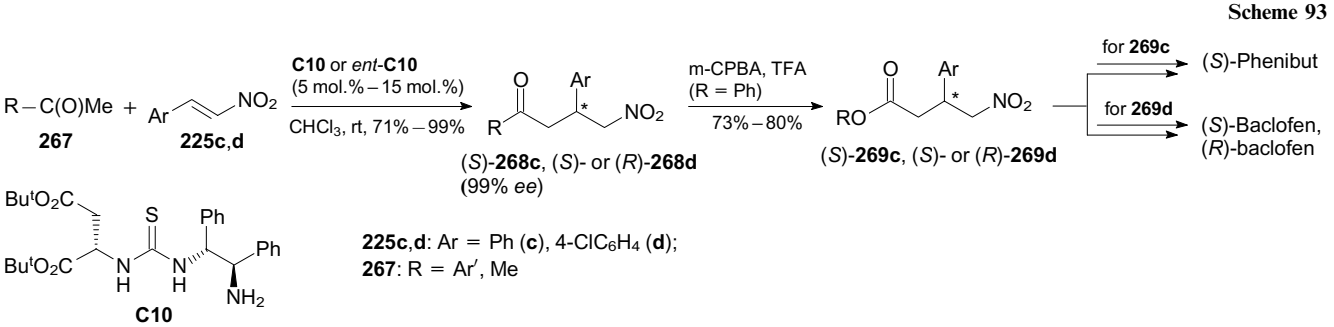
Py = 2-pyridyl
m-CPBA is *meta*-chloroperoxybenzoic acid

Scheme 92



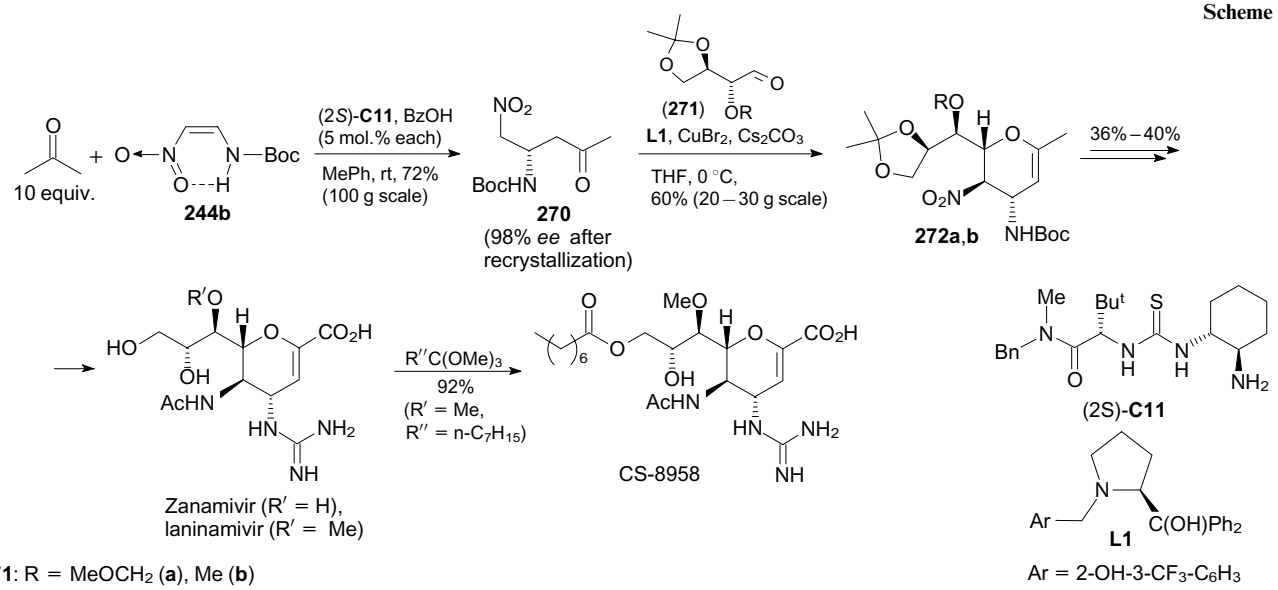
225b: Ar = 4-$MeOC_6H_4$; Cbz is benzyloxycarbonyl, DBU is 1,8-diazabicyclo[5.4.0]undec-7-ent, MS is mesyl

Scheme 93



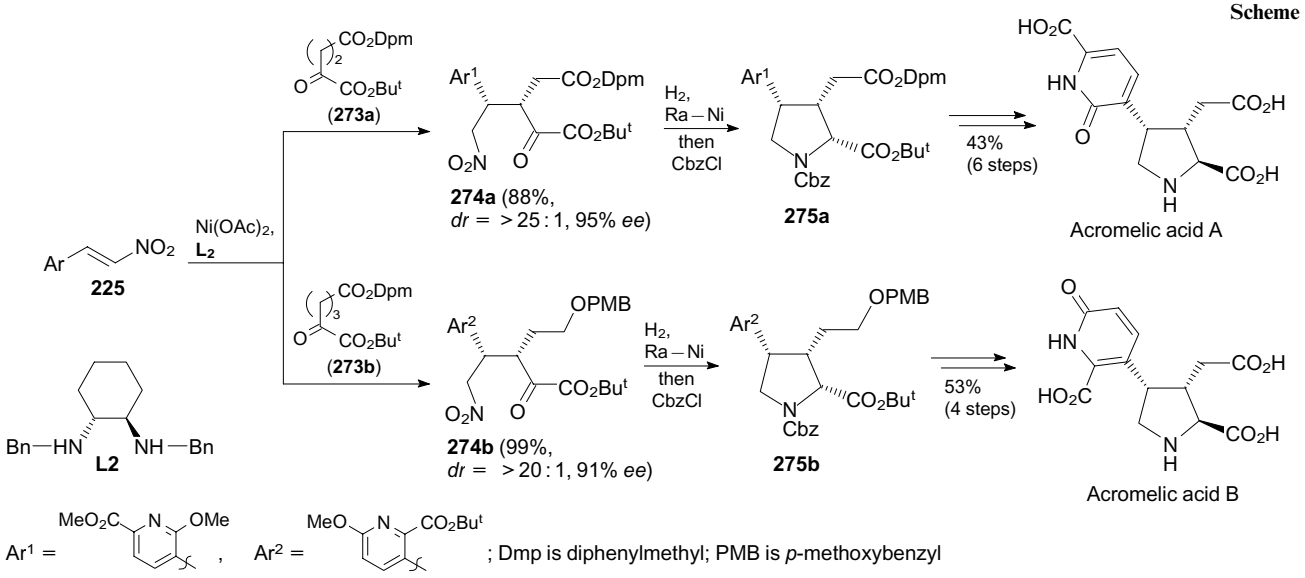
225c,**d**: Ar = Ph (**c**), 4-ClC_6H_4 (**d**);
267: R = Ar′, Me

Scheme 94



271: R = $MeOCH_2$ (**a**), Me (**b**)

Scheme 95



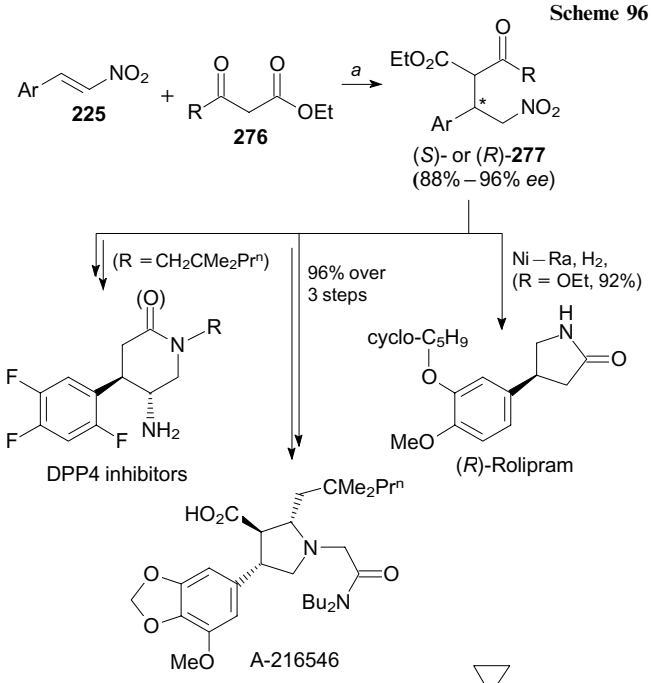
reaction catalyzed by a copper complex with α,α-diphenylprolinol ligand **L1**. The authors succeeded in finding the conditions for the synthesis of nitroketone **270** in an amount of up to 100 g per batch with 98% *ee* (Scheme 94). High *anti* selectivity of the Henry reaction was provided by the use of aldehyde ethers **271a** and **271b** bearing small protecting groups (methoxymethyl or methyl) as the substrates. Nitropyran derivatives **272a** and **272b** were converted to the drugs zanamivir and laninamivir in several steps in 36% – 40% overall yield. The esterification of the terminal hydroxy group in laninamivir gave the inhibitor CS-8958.

Ouchi *et al.*[313] reported the procedure for the asymmetric addition of α-keto esters **273a**,**b** to nitroolefins **225** (2,6-dichloropyridine derivatives) in the presence of Ni complexes with chiral diamine **L2**. The authors applied this procedure to synthesize acromelinic acids A and B, natural products isolated from the plant *Clitocybe acromelalga*,[314] which are capable of activating ionotropic glutamate receptors in the brain.[315, 316] Under the optimal conditions, the reaction stereoselectively produced Michael adducts **274a** and **274b** (Scheme 95). The reduction of the nitro group in the latter compounds afforded pyrrolidine derivatives **275a** and **275b**. The synthesis of the target products was completed by the transformation of the functional groups and the base-promoted epimerization of the stereogenic centre C(2) of the pyrrolidine ring.

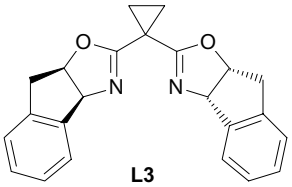
3.2.2. Asymmetric reactions of nitroolefins with 1,3-dicarbonyl compounds

The stereoselective addition of malonic and acetoacetic acid derivatives to nitroolefins in the presence of chiral catalysts provides the basis for a number of up-to-date approaches to γ-nitrocarboxylic acid derivatives, which are close precursors of GABA analogues and natural γ- and δ-lactones. Barnes *et al.*[317] found that β-keto esters and malonates **276** react with nitroolefins **225** in the presence of the Mg^{II} – bis(oxazoline) ligand **L3** (*ent*-**L3**) – *N*-methylmorpholine (NMM) (4 mol.% – 5 mol.%) catalytic system to form Michael adducts **277** with high enantioselectivity (up to 96% *ee*) in high yields (Scheme 96). The catalytic reduction of the nitro group (H_2/Raney Ni) and subsequent trivial transformations gave dipeptidyl peptidase IV (DPP4)

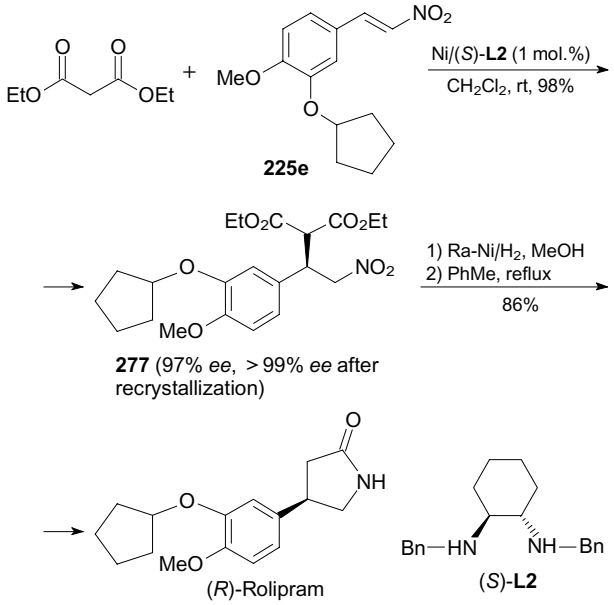
Scheme 96



(*a*) **L3** or *ent*-**L3** (4 mol.%), $Mg(OTf)_2$ (4 mol.%), NMM (5 mol.%), MS, $CHCl_3$ (82% – 95% yield); **276**: R = OEt, $CH_2CMe_2Pr^n$; NMM is *N*-methylmorpholine, MS is molecular sieves



Scheme 97

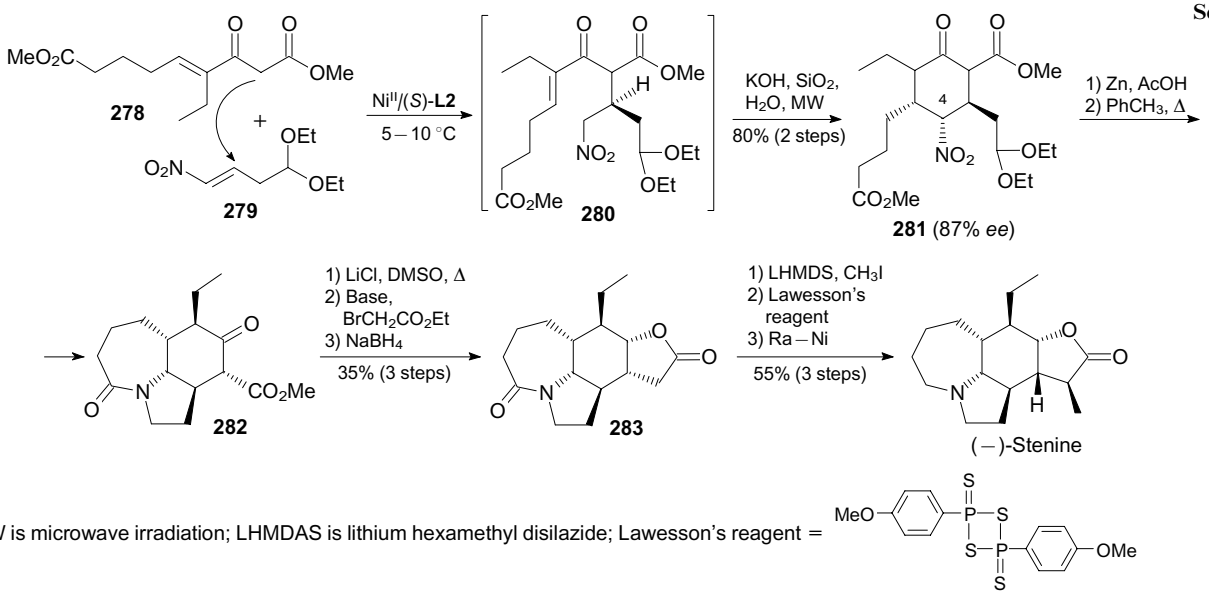


inhibitors,[318] endothelin-A receptor agonist A-216 546 (Ref. 319) and the most active (*R*)-enantiomer of the antidepressant rolipram.

A Ni^{II} complex with (*S*,*S*)-1,2-diaminocyclohexane derivative **L2** (Evans catalyst) is an even more efficient catalyst for the asymmetric Michael reaction of nitroolefins with malonates.[320] Thus, Michael adduct **277** is produced from diethyl malonate and nitrostyrene **225e** in quantitative yield with 97% *ee* in the presence of as low as 1 mol.% of this catalyst (Scheme 97). The method enables the production of kilogram batches of the adduct. It should be noted that diamine **L2** can be regenerated from the reaction mixture and reused up to five times in subsequent reactions. The latter fact, along with a small amount of the catalyst used, is important for implementation of the method in industry. The hydrogenation/cyclization of compound **277** in the presence of Ra-Ni and the subsequent thermal decarboxylation gave enantiomerically pure (*R*)-rolipram.

Zhang and co-workers[321] applied a similar procedure to prepare the cyclohexane moiety of the alkaloid (–)-stenine naturally occurring in the roots of the *Stemona* species.[322] The synthetic sequence starts with the Ni^{II}–(*S*)-**L2**-catalyzed asymmetric addition of unsaturated β-keto ester **278** to functionalized nitroalkene **279** (Scheme 98). The microwave-assisted treatment of crude nitroenone **280** with the $KOH–SiO_2$ system resulted in the stereoselective cyclization of **280** to nitrocyclohexane **281** (87% *ee*). The latter was reduced (Zn – AcOH) to tricyclic lactam **282**, which was

Scheme 98

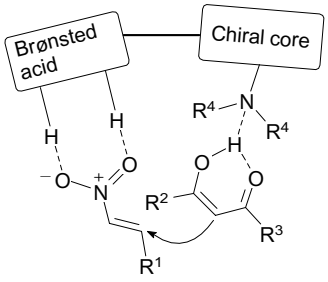


MW is microwave irradiation; LHMDAS is lithium hexamethyl disilazide; Lawesson's reagent =

subjected to decarboxylation, alkylation and reduction to form tetracyclic lactam **283** as a precursor of the target alkaloid.

A promising approach to asymmetric reactions of 1,3-dicarbonyl compounds with nitroalkenes is based on the use of metal-free catalysts (organocatalysts). A high level of stereoinduction is achieved, in particular, in the presence of bifunctional tertiary amines containing Brønsted acid moieties in the chiral core (Scheme 99). The tertiary amino group facilitates the enolization of the dicarbonyl compound, while the nearby hydrogen donor (a thiourea, urea, hydroxy group or a squaramide moiety) controls the trajectory by which the reagents are brought into direct contact through stereospecific hydrogen bonds with oxygen atoms of the nitro group in the transition state of the catalytic reaction.[323 – 325]

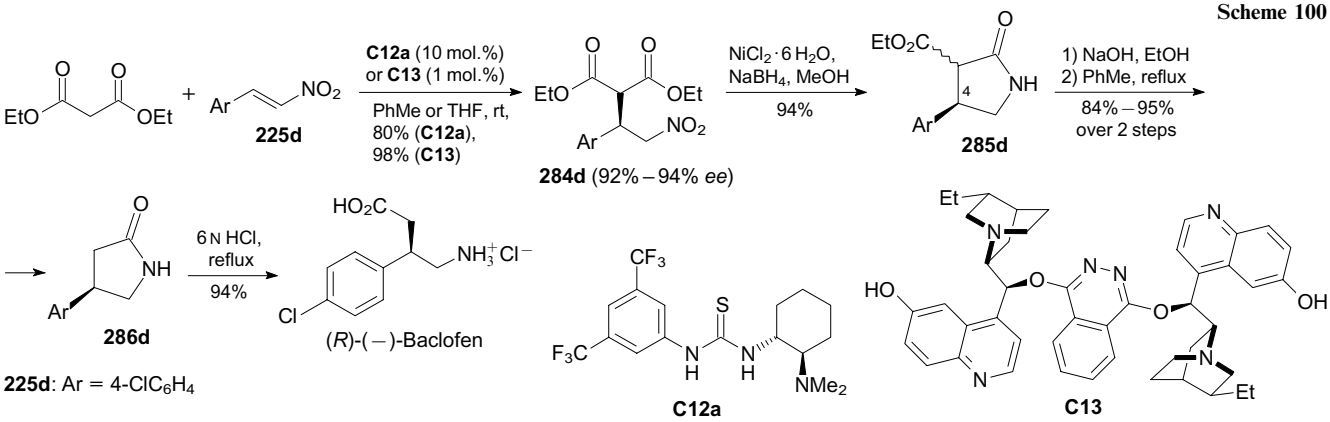
Scheme 99



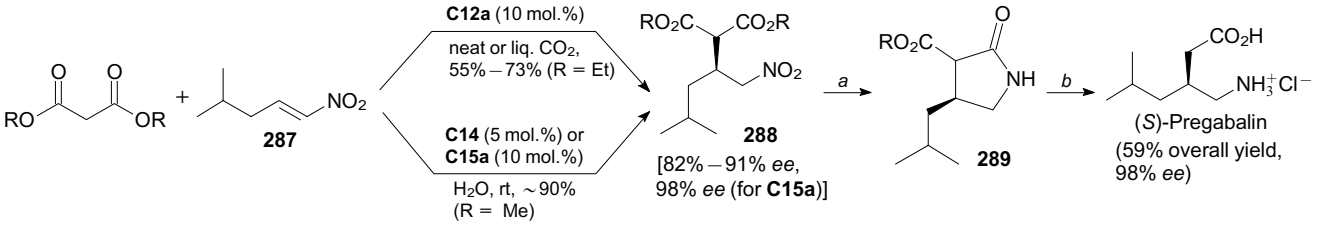
Takemoto and co-workers[326, 327] found that nitroolefin **225d** reacts with diethyl malonate in the presence of the thiourea-containing bifunctional catalyst **C12a** (10 mol.%) to give adduct **284d** in 80% yield with 94% *ee* (>99% *ee* after crystallization) (Scheme 100). The reduction of the nitro group in **284d** was accompanied by cyclization to lactam **285d**. The ester group was removed from the latter compound by alkaline hydrolysis and thermal decarboxylation. The pyrrolidine ring opening of compound **286d** (6 N HCl) afforded the active (*R*)-enantiomer of the antidepressant baclofen in 59% overall yield with respect to nitroolefin **225d**. The reaction of **225d** with diethyl malonate can also be performed in the presence of the C2-symmetric dihydroquinine derivative (dihydroquinidine) **C13** as the catalyst.[328]

Li and co-workers[329] developed a convenient method for the synthesis of the antiepileptic drug (*S*)-pregabalin based on the **C12a**-catalyzed asymmetric reaction of nitroalkene **287** with diethyl malonate. This reaction occurs under solvent-free conditions and gives adduct **288** in 73% yield with 88% *ee* (Scheme 101). The hydrogenation/lactamization of adduct **288** with Ra – Ni afford pyrrolidinone **289** (98% *ee* after crystallization). The authors succeeded in combining the decarboxylation and lactam ring opening reactions in a single process by performing acid hydrolysis of compound **289** under severe conditions (6 N HCl, 100 °C). As a result (*S*)-pregabalin hydrochloride was produced in 92% yield (44% with respect to **287**) with

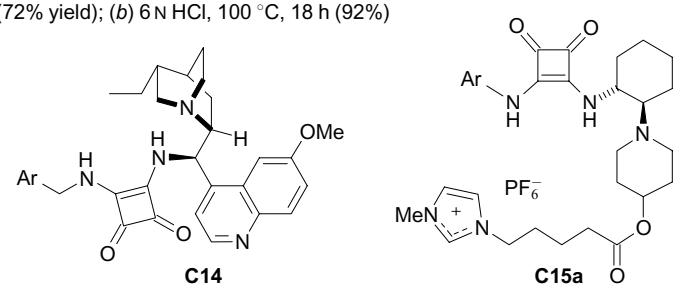
Scheme 100



Scheme 101



(*a*) Ra – Ni, H_2, MeOH, rt (72% yield); (*b*) 6 N HCl, 100 °C, 18 h (92%)



C14, **C15a**: Ar = 3,5-$(CF_3)_2C_6H_3$

98% *ee*. It is worth noting that the (*S*)-enantiomer of pregabalin exhibits required pharmacological properties, whereas the (*R*)-enantiomer is virtually inactive.[330]

Zlotin and co-workers[331] modified this method by performing the **C12a**-catalyzed Michael reaction in liquid carbon dioxide. The proposed modification is preferable in terms of pharmacology because it minimizes the risk of contamination of target drug with organic solvents and simplifies the isolation of the product (decompression). Bae and Song[332] found that adduct **288** can be synthesized with high enantioselectivity (91% *ee*) from **287** and dimethyl malonate in an aqueous suspension in the presence of hydrophobic squaramide-containing dihydroquinidine derivative **C14** ('on water' reactions).[333] Specially for this type of reactions, Zlotin and co-workers[334] recently synthesized hybrid catalyst **C15a** modified with an amphiphilic ionic group. This group holds the catalyst at the interface between the organic (reagents) and aqueous phases, thereby providing high enantiomeric purity of adduct **288** (98% *ee*). In this case, heterogeneous catalyst **C15a** is easily separated from the product and can be reused in the reaction (up to 30 times) (see Scheme 101).

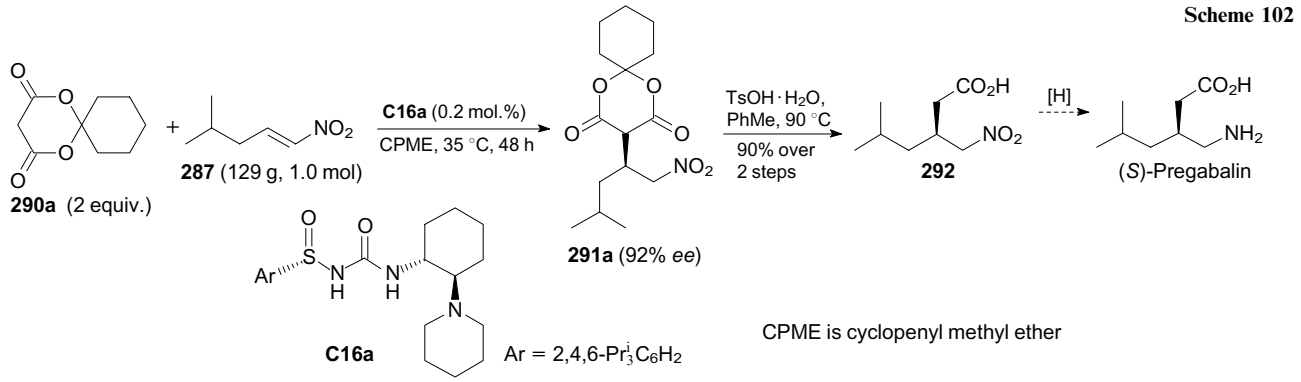
In an alternative method for the synthesis of pregabalin proposed by Ellman and co-workers,[335] bicyclic Meldrum's acid **290a** serves as the nucleophile and *N*-sulfinylurea-containing piperidine derivative **C16a** acts as the catalyst (Scheme 102). The required amount of the catalyst **C16a** in the reaction between **287** and **290a** is as low as 0.2 mol.%. Crude product **291a** was used *in sit*u in the TsOH-promoted hydrolysis/decarboxylation cascade reaction to produce ~150 g of key intermediate **292** (90% yield) in one batch.

The asymmetric reaction of nitroalkene **287** with Meldrum's acid **290b** in the presence of thiourea-containing 9-amino-(9-deoxy)epiquinidine derivative **C17** occurred with lower selectivity and gave adduct **291b** with enantiomeric purity of 74% *ee* (Scheme 103).[336] The hydrogenation of compound **291b** (Ra-Ni) produced amino diacid **293**, which was transformed into (*S*)-pregabalin hydrochloride (80% *ee*) *via* decarboxylation. The use of squaramide-containing tertiary amine (*R*,*R*)-**C15b**[337] (an efficient chiral inductor in the asymmetric catalysis[338]) as the catalyst resulted in an increase in enantiomeric purity of adduct **291b** to 94%, although with a certain loss in the overall yield of (*S*)-pregabalin (52% instead of 59%).

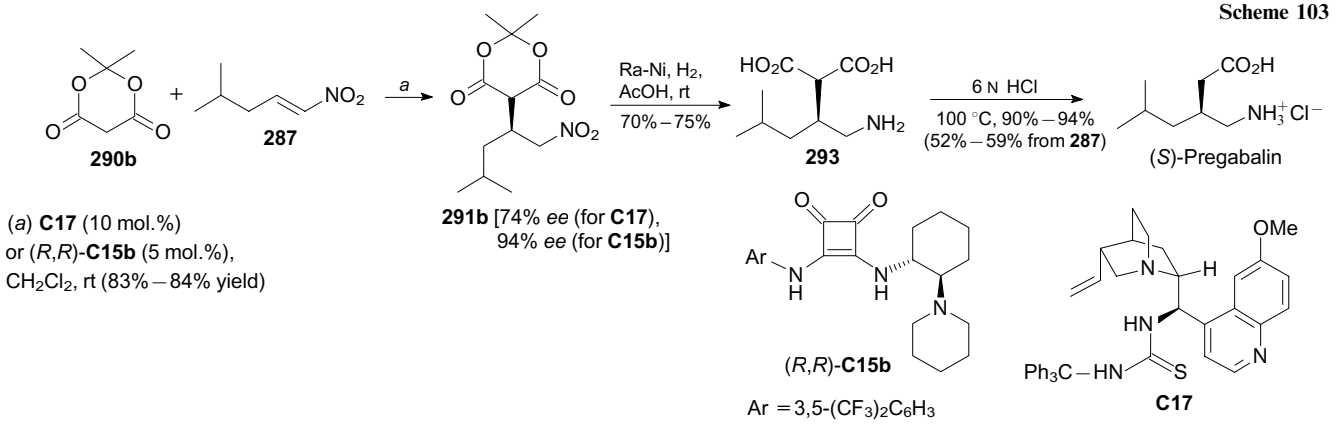
Dixon and co-workers[339] employed available nitroolefins in the asymmetric synthesis of the antidepressant (*R*)-rolipram[340] and the selective serotonin reuptake inhibitor (3*S*,4*R*)-paroxetine[341] (Scheme 104). In the presence of cinchonine-containing thiourea **C18a**, nitroolefins **225e** and **225f** react with dimethyl malonate to form adducts **284e** and **284f** with high enantioselectivity (92% – 94% *ee*) and in higher yield than in the thiourea **C12a**-catalyzed reaction (see Scheme 100). Enantiomerically pure products **284** were obtained by crystallization. The reduction of the nitro group in compound **284e** with nickel boride afforded γ-lactam **285e**, which was subjected to hydrolysis and decarboxylation to afford (*R*)-rolipram (86% yield over 4 steps). The transformation of adduct **284f** into paroxetine required the homologization by means of the Mannich reaction and the subsequent removal of nitro and alkoxycarbonyl groups from δ-lactam **294**. Piperidone **295** thus obtained was transformed into (3*S*,4*R*)-paroxetine by known methods.[342]

In some cases, dithiomalonates can be considered as promising nucleophilic substrates in catalytic asymmetric reactions with nitroolefins. The resulting sulfur-containing analogues of adducts **284** can easily be converted to the above-considered drugs by reductive desulfuration.[343, 344]

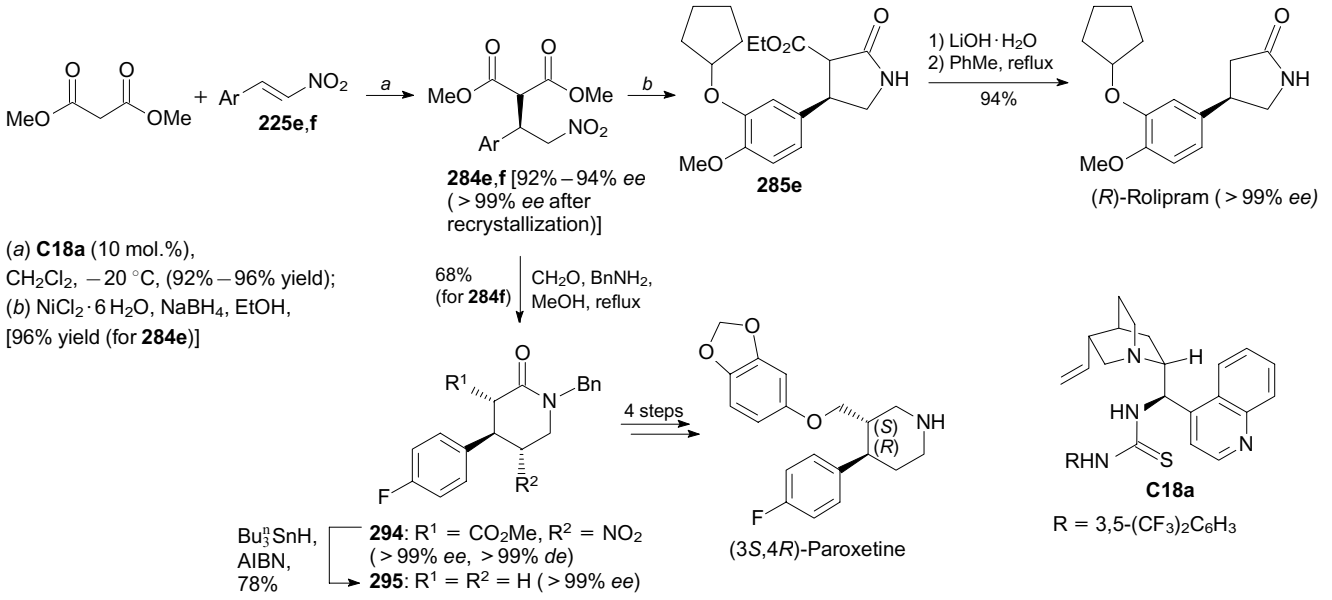
Scheme 102



Scheme 103



Scheme 104



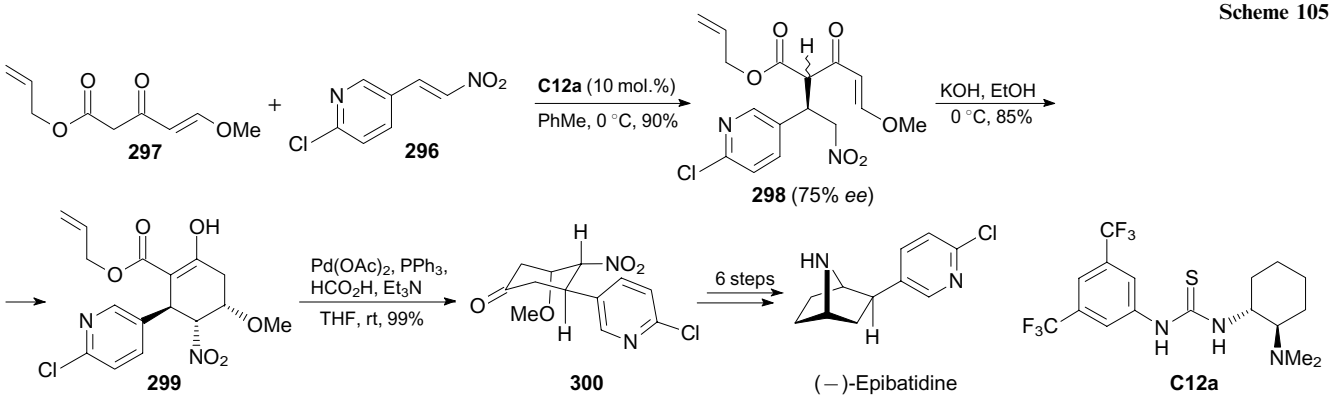
Asymmetric reactions of nitroolefins with 1,3-dicarbonyl compounds are used not only to prepare GABA analogues but for the synthesis of other useful biologically active substances. Takemoto and co-workers [345] applied the reaction of nitroolefin **296** with γ,δ-unsaturated β-keto ester **297** to synthesize a precursor of the alkaloid (−)-epibatidine. This reaction catalyzed by chiral thiourea **C12a** (10 mol.%) afforded enantiomerically enriched (75% *ee*) adduct **298** (Scheme 105). The latter was converted to diastereomerically pure cyclic keto ester **299**, which was subjected to Tsuji-type [346] deallyloxycarbonylation to give precursor **300** of (−)-epibatidine (99% yield).

Jørgensen and co-workers [347] synthesized functionalized γ-butyrolactones (regulators of metabolism of *Streptomyces* bacteria) that are used as antibiotics.[348] The key step was the asymmetric addition of β-ketoamides **301** to γ-silyloxynitroalkene **302** in the presence of quinine thiourea catalyst **C5**. In this case, adducts **303** were obtained as mixtures of diastereomers (*dr* = 3 : 1 – 4 : 1). However, their lactonization products **304** were isolated as single diastereomers with 85% – 90% *ee*. Lactones **304** were converted to the regulators VB-D and IM-2 by trivial transformations of functionalities (Scheme 106).

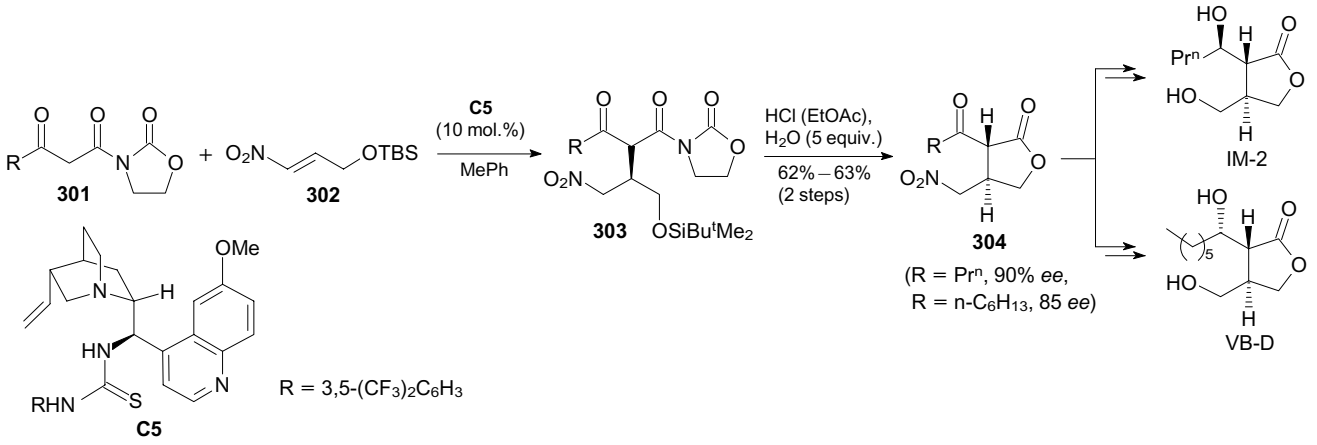
Dixon and co-workers [349] accomplished the total synthesis of the alkaloid (−)-nakadomarin A, a naturally occurring compound, which was extracted from the sponge *Amphimedon sp*. collected at the seashore of the Okinawa Island (Japan). This heterocyclic alkaloid exhibits cytotoxicity against mouse lymphoma L1210 cells and inhibits cyclin-dependent kinase 4.[350] The key stereocentres were created during the synthesis of adduct **307** (*dr* 10 : 1) from chiral 1,3-dicarbonyl compound **305** and furan-containing nitroolefin **306** in the presence of cinchonine-derived urea catalyst **C18b** (Scheme 107). Adduct **307** was converted to spiro compound **308** by the three-component Mannich reaction accompanied by lactamization. The selective reduction of the nitro group in **308** with AIBN – Bu_3SnH gave intermediate **309**, which was transformed into (−)-nakadomarin A *via* reduction, cyclization and metathesis. However, the double bond formation in the macrocycle was not selective, and the reaction product was obtained as a mixture of *Z* and *E* isomers.

Later, this research team [351] significantly improved the *Z*-selectivity of the (−)-nakadomarin A synthesis. In this synthetic approach, pyrrolidinooxazolidine **310** served as the pronucleophile in the key stereodetermining step, and

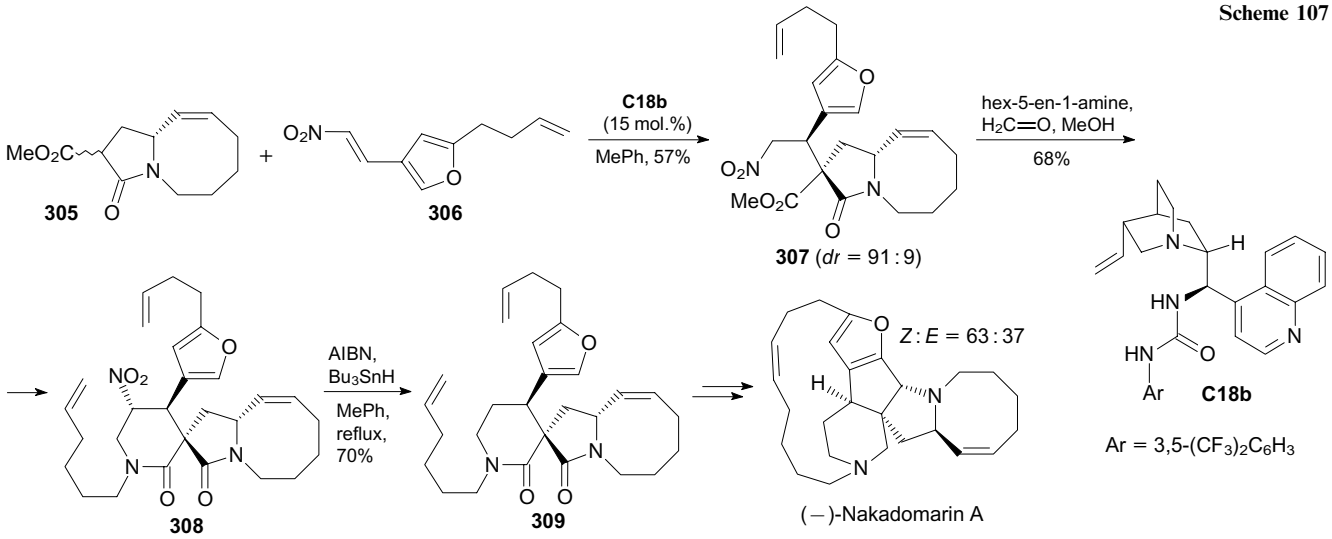
Scheme 105



Scheme 106



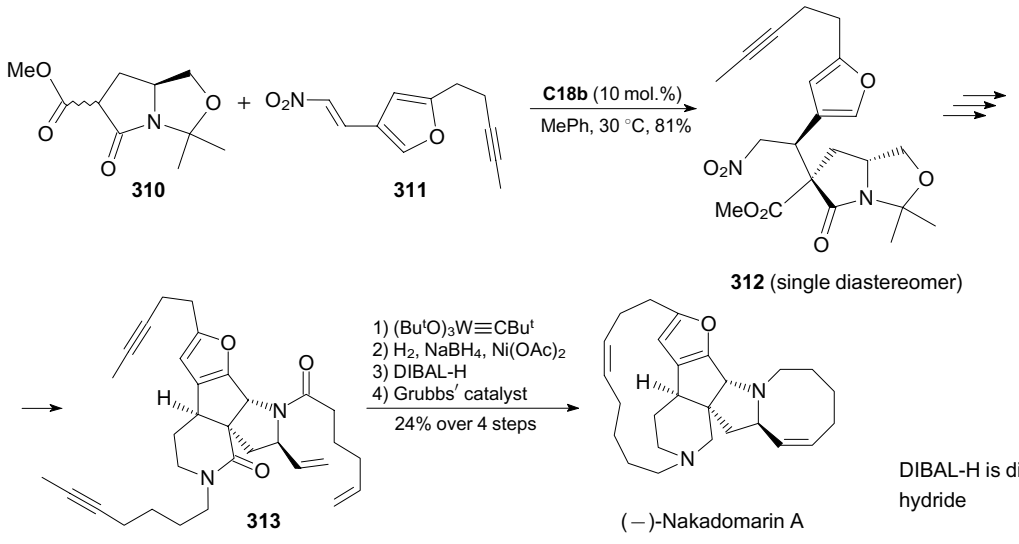
Scheme 107



AIBN is azobis(isobutyronitrile)

compound **311** bearing an alkyne group in the side chain was used as the nitroolefin. The authors succeeded in preparing adduct **312** as a single diastereomer and transformed the latter into compound **313** in several elegant synthetic steps. Compound **313** contains the tetracyclic alkaloid core and the required alkene and alkyne groups at the periphery (Scheme 108). The subsequent formation of two macrocycles in the presence of Schrock and Grubbs

Scheme 108



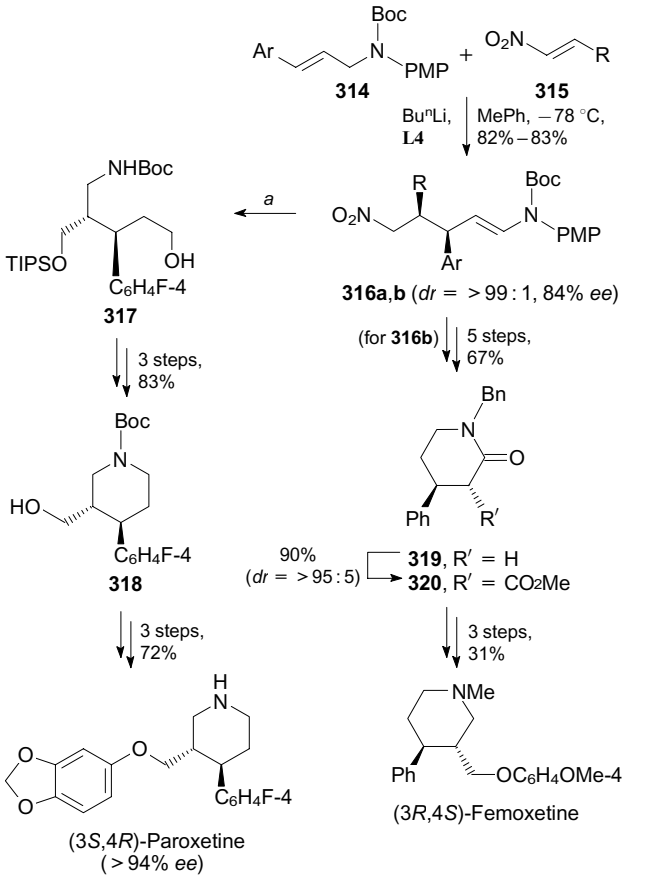
DIBAL-H is diisobutylaluminium hydride

catalysts, *cis*-hydrogenation of the triple bond and the reduction of lactam groups completed the total synthesis of (−)-nakadomarin A.

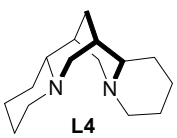
3.2.3. Asymmetric reactions of nitroolefins with other *C*-nucleophiles

Some *C*-nucleophiles, which do not formally belong to carbonyl or 1,3-dicarbonyl compounds, are also involved in stereoselective catalytic reactions with nitroolefins. Johnson *et al.*[352] found that anions, generated from allylamines **314** under the action of Bu^{n}Li, add to nitroalkenes **315** in the presence of (−)-sparteine ligand **L4** to afford *syn* isomers of adducts **316** with 84% *ee*. This procedure was applied to synthesize the antidepressants (−)-paroxetine and (+)-femoxetine (Scheme 109). First, the protected amino group in compound **316a** was transformed into a hydroxy group, while the nitro group was converted to a Boc-protected amino group *via* hydrolysis, reduction and *N*-Bocylation giving amino alcohol **317**. The cyclization and silyl deprotection afforded piperidine **318**, which was transformed into (3*S*,4*R*)-paroxetine by standard methods. (+)-Femoxetine, which has opposite configurations at stereocentres, was synthesized in a similar way from enecarbamate **316b** through the formation of piperidone **319** and the corresponding carboxylate **320**.[353]

Scheme 109

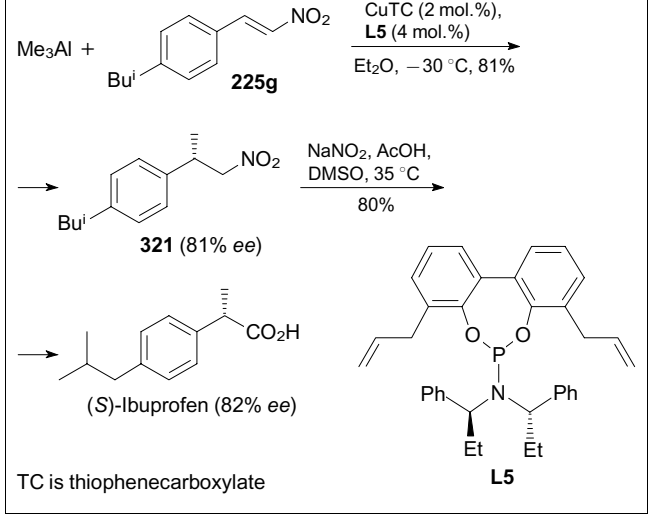


(*a*) 1) HCl; 2) $NaBH_4$; 3) Pd/C, HCO_2NH_4; 4) Boc_2O; 83% (for **316a**); **316**: R = CH_2OTIPS, Ar = 4-FC_6H_4 (**a**); R = H, Ar = Ph (**b**); Boc is *tert*-butoxycarbonyl; TIPS is triisopropylsilyl



Polet and Alexakis[354] proposed a procedure for the enantioselective methylation of nitroolefins with trimethylaluminium in the presence of a copper complex and applied this method to synthesize the non-steroidal anti-inflammatory drug (+)-ibuprofen.[355] The active complex was generated from thiophenecarboxylic acid salt (CuTC) (2 mol.%) and chiral phosphoramidite ligand **L5** (4 mol.%) under the reaction conditions. β-Methylation product **321** was synthesized from nitroolefin **225g** in 81% yield with acceptable selectivity for this type of reactions (81% *ee*) (Scheme 110). Adduct **321** was converted to (+)-ibuprofen under the action of $NaNO_2$ – AcOH in DMSO.

Scheme 110

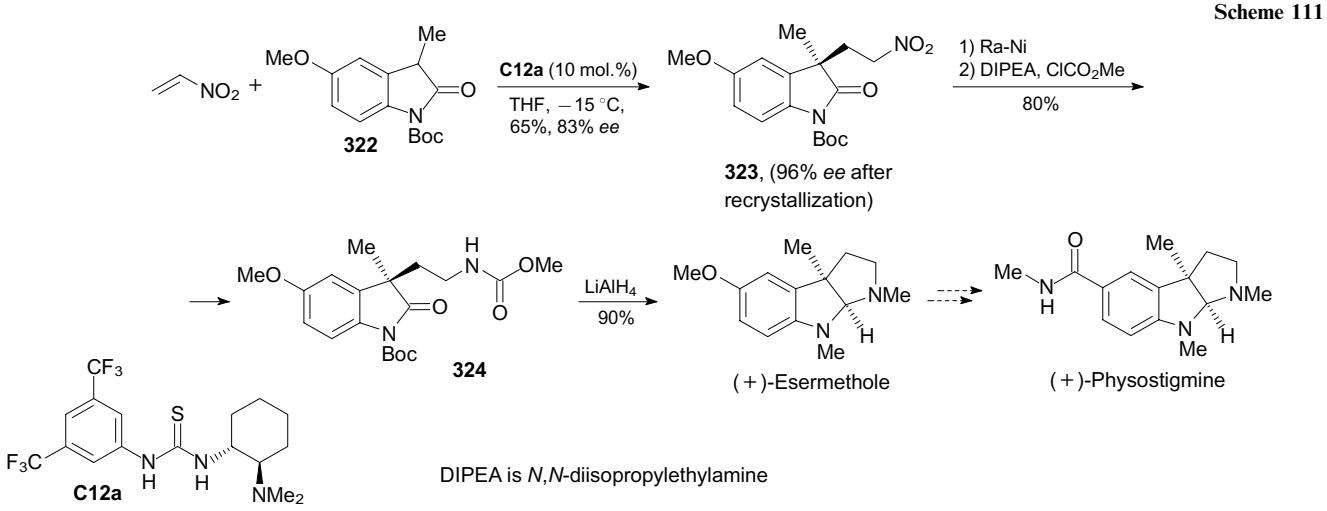


Barbas III and co-workers[356] found that 2-oxindole derivatives, heterocyclic systems found in a wide range of drugs and natural alkaloids, can act as nucleophiles in asymmetric reactions with nitroalkenes. Thus, in the presence of thiourea derivative **C12a**, *N*-Boc-protected 3-methyl-2-oxindole **322** reacts with nitroethylene to form adduct **323** in 65% yield with 83% enantioselectivity, which is increased to 96% after crystallization (Scheme 111). The catalytic reduction (Ra-Ni) of the nitro group in adduct **323** and subsequent carbamoylation afford compound **324**, which is converted into (+)-esermethole *via* reductive cyclization. The latter compound can be transformed by known methods[357,358] into the alkaloid (+)-physostigmine, as an acetylcholinesterase inhibitor extracted from the seeds of the African plant *Physostigma venenosum*.[359]

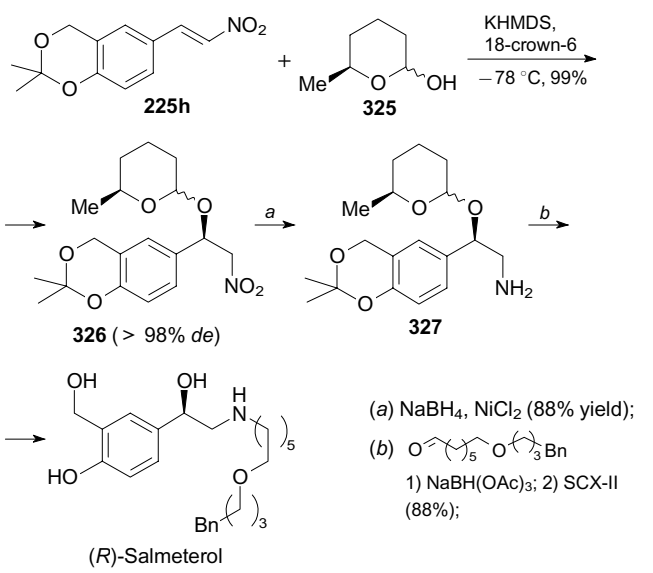
3.2.4. Asymmetric reactions of nitroolefins with heteronucleophiles

The asymmetric conjugate addition of *O*-, *N*- and *S*-nucleophiles to nitroolefins provides a direct route to the stereoselective synthesis of pharmacologically valuable vicinal amino alcohols, diamines and thioamines (see reviews[19,256–259,360]). Dixon and co-workers[361] developed a simple method for the asymmetric synthesis of the anti-asthmatic drug (*R*)-salmeterol based on the diastereoselective addition of chiral δ-lactol (*S*)-**325** to nitroolefin **225h** (Scheme 112). Under the proposed conditions (KHMDS – 18-crown-6), nitro ether **326** was prepared in quantitative yield with > 98% *de*.[362] The reduction of the nitro group in **326** afforded protected amino alcohol **327**,

Scheme 111

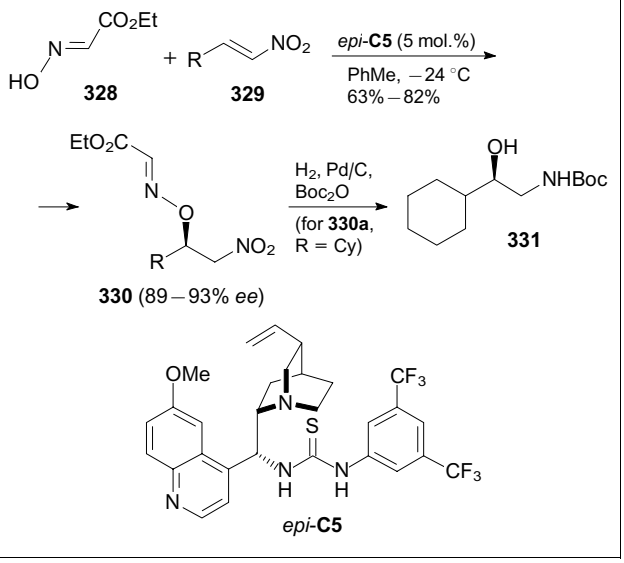


Scheme 112



SCX-II is Silica-supported propylsulfonic acid;
KHDMS is potassium hexamethyldisilazane

Scheme 113



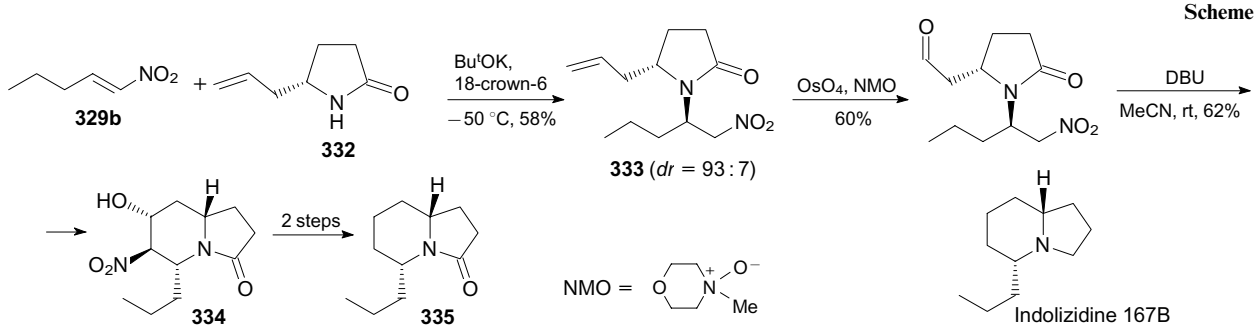
which was transformed into (*R*)-salmeterol by standard methods.

Jørgensen and co-workers[363] found that enantioselective reactions of *O*-nucleophiles with nitroalkenes can be performed in the presence of organocatalysts. Thus, in the presence quinine-thiourea *epi*-**C5** (5 mol.%) as the catalyst, ethyl glyoxylate oxime **328** adds to nitroalkenes **329** to form adducts **330** with up to 93% *ee* (Scheme 113). In this case, bifunctional catalyst *epi*-**C5** activates both reactants: oxime **328** *via* hydrogen bonding with the quinuclidine nitrogen atom and nitroalkene **329** *via* hydrogen bonding with a thiourea moiety. This method was used, in particular, to prepare cyclohexane derivative **330a** (R = Cy). The latter is a direct precursor of amino alcohol **331**, the deprotected form of which exhibits adrenomimetic properties.[364]

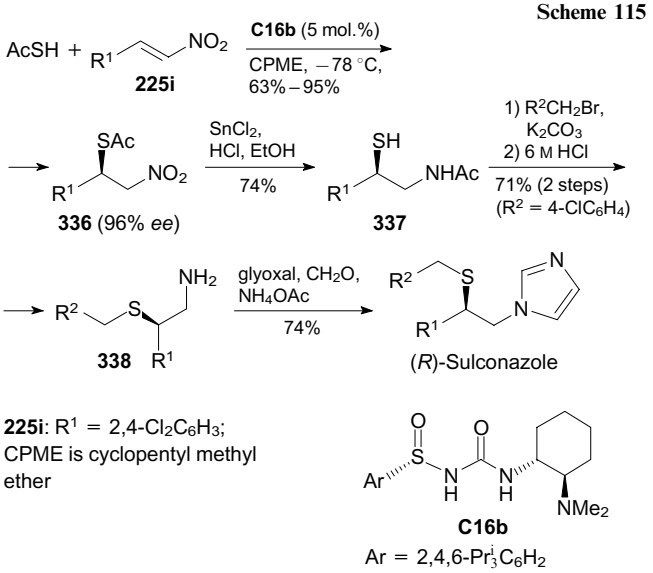
Kamimura *et al.*[365] accomplished a formal synthesis of the indolizidine alkaloid 167B.[366] The proposed approach is based on Bu^{t}OK-promoted formation of the stereocentre at the β position to the nitro group *via* the addition of chiral pyrrolidin-2-one **332**, as a *N*-nucleophile, to 1-nitropentene (**329b**) (Scheme 114). Adduct **333** was synthesized in moderate yield but with high stereoselectivity (*dr* = 93 : 7). The oxidation of the terminal double bond followed by the stereospecific intramolecular Henry reaction afforded bicyclic compound **334**. The stepwise removal of hydroxy and nitro groups resulted in the formation of indolizidinone **335** as a precursor of indolizidine 167B. Stereoselective approaches to the synthesis of a number of other pharmacologically valuable nitrogen-containing heterocyclic systems, in particular using nitroolefins, are considered in a recent review.[367]

The asymmetric addition of *S*-nucleophiles to nitroolefins provides a route to the synthesis of compounds containing the 1,2-aminosulfanyl moiety, which is present in the naturally occurring amino acid taurine, penicillin antibiotics, biotin, the antifungal agent sulconazole, *etc.*[368, 369] Ellman and co-workers[370, 371] found that in these reactions, thioacetic acid can act as a nucleophile, while bifunctional *N*-sulfinylurea **C16b** containing a chiral sulfur atom serves as the catalyst.[372] Under the proposed conditions, 2,4-dichloronitrostyrene **225i** was enantioselectively (96% *ee*) converted to β-nitroethanethiol derivative **336** (Scheme 115). The subsequent reduction of the nitro

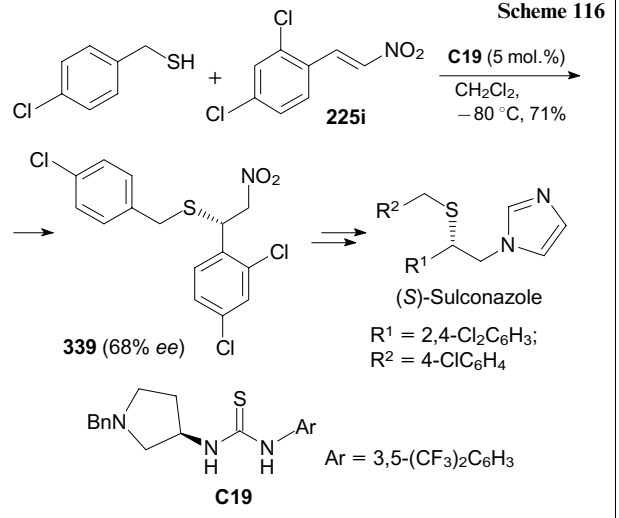
Scheme 114



Scheme 115



Scheme 116



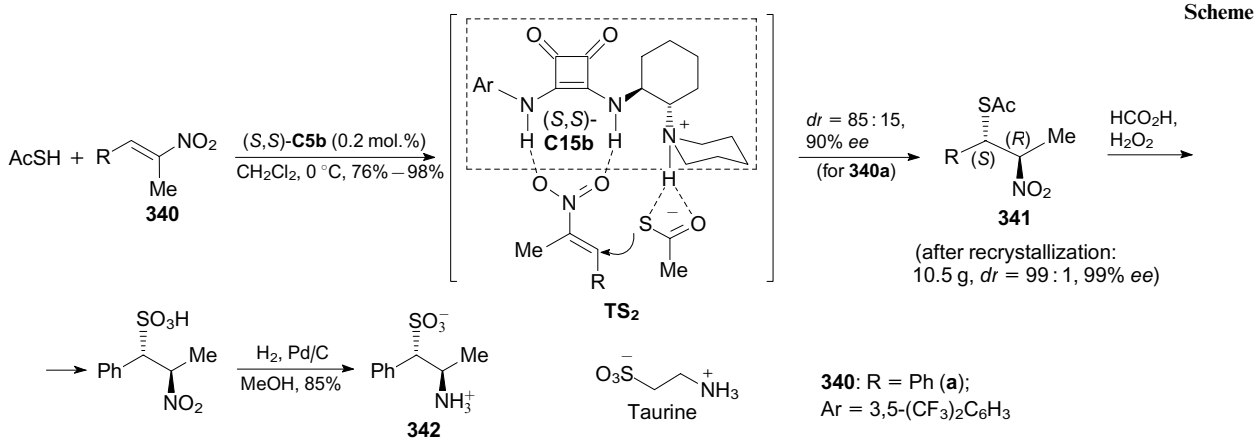
group to the acetylamino group, alkylation of aminothiol **337** with 4-chlorobenzyl bromide, deacylation and transformation of the amino group in compound **338** into the imidazole ring gave the (*R*)-enantiomer (96% *ee*) of the fungicide sulconazole in 32% yield with respect to nitroolefin **225i**.

An even more simple (3 steps) method for the synthesis of sulconazole [in this case, of its (*S*)-enantiomer] is based on the direct addition of 4-chlorobenzylthiol to nitrostyrene **225i** in the presence of bifunctional thiourea **C19** linked to the pyrrolidine ring.[373] This method allowed asymmetric synthesis of Michael adduct **339** in good yield (71%), but the enantiomeric excess was rather low 68% (Scheme 116).

The subsequent reduction of the nitro group and the formation of the imidazole ring gave the target (*S*)-sulconazole.

Yang and Du[374] succeeded in performing asymmetric thiolation of α,β-disubstituted nitroolefins **340** with AcSH using squaramide-containing (*S*,*S*)-diaminocyclohexane **C15b** as the catalyst. In the presence of as low as 0.2 mol.% of this catalyst, the corresponding β-nitro sulfides **341** are produced in high yield with efficient stereoselectivity (up to 94 : 6 *dr* and 95% *ee*) (Scheme 117). The high activity and good stereocontrol were attributed to the involvement of all nitrogen-containing functional groups of the catalyst **C20** in hydrogen bonding with the reactants in the transition state **TS$_2$**, in the reaction. The method enabled the synthesis of enantiomerically pure (after crys-

Scheme 117



tallization) adduct **341** in an amount of 10.5 g in one batch. The subsequent oxidation of the acetylthio group and reduction of the nitro group afforded compound **342**, a derivative of the naturally occurring amino acid taurine used for the treatment of eye and cardiovascular diseases and type I and II diabetes mellitus.[375]

Therefore, the catalytic methods for the stereoselective functionalization of nitroolefins developed in recent years have a great synthetic potential. They enable the synthesis of a broad range of analogues of natural compounds and valuable drugs of high molecular complexity using simple and available starting compounds. It can be expected that, in the near future, these methods will be used in innovative technologies to produce the most active pharmaceutical ingredients for the treatment of widespread diseases of high consequence.

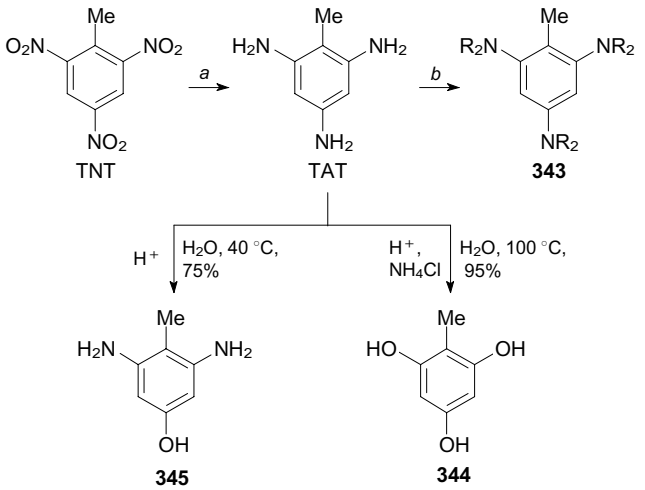
3.3. New transformations of nitroarenes

Aromatic polynitro compounds are widely used not only as energetic (explosive) substances but also as valuable precursors for the preparation of a broad range of products for civilian applications. The importance of this research area became apparent in the 1980 – 1990s, when the community faced the problem of conversion of expired TNT.

Systematic research on the chemical utilization of demilitarized TNT resulted in the development of an approach for the conversion of TNT into a dual-use product. The transformation of TNT into 2,4,6-triaminotoluene (TAT) as a key synthon for the preparation of various valuable compounds (Scheme 118) holds the most promise. Compound **343** generated by exhaustive oxypropylation of TAT[376] is used as a cross-linking agent for polyurethane foams. Besides, TAT served as the basis for the preparation of 2,4,6-trihydroxytoluene (**344**)[377] and 2,6-diamino-4-hydroxytoluene (**345**)[378] as precursors for the synthesis of azo dyes and azo pigments.[379] 2,4,6-Trinitrotoluene and its derivatives were used in the synthesis of condensation monomers for organosoluble polyimides and polyamides with high thermal stability.[380 – 382]

Researchers at the ZIOC RAS have performed a series of studies on nitroarenes as versatile reagents for the synthesis of various biologically active substances.[383,384] Nitroarenes are characterized by the ability to form stable σ-adducts with nucleophiles. Stability of these complexes increases in the presence of two *meta*-nitro groups. On the other hand, the nitro group is a good leaving group that is capable of being replaced by different nucleophiles. These reactions are particularly efficient with polynitroarenes. For instance, the reactions of trinitrobenzene (TNB), TNT and some other polynitroarenes with thiols, phenols and azoles in the presence of bases afford products **346** – **348**, in which one or several nitro groups are replaced by nucleophiles depending on the reaction conditions and amounts of reagents (Scheme 119). Generally, the nitro group in the *ortho* position to the substituent R is replaced first.[385 – 390]

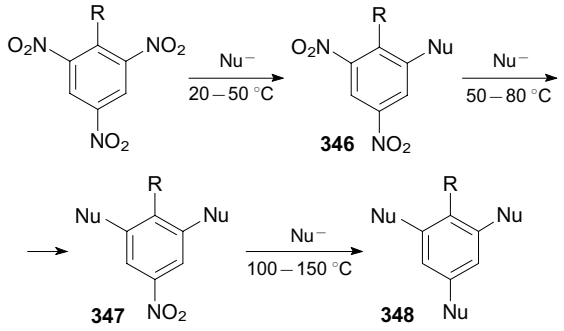
Scheme 118



(*a*) H_2, Pd/C, MeOH, 60 °C, 0.1 – 0.6 MPa (95% – 97% yield);

(*b*) , H_2O, 60 °C; **343**: R = $CH_2CH(OH)Me$

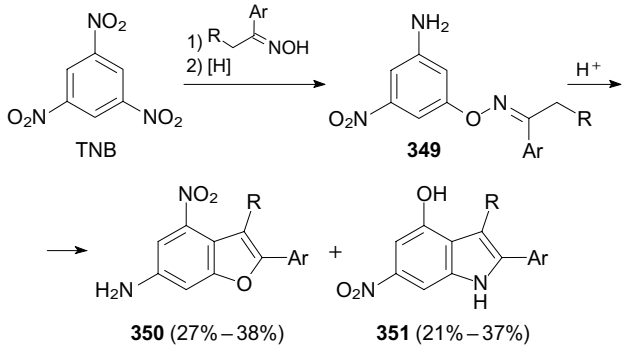
Scheme 119



R = H, Me, CH=CHAr, CH=NAr, C(O)R′, *etc.*;
Nu = OAr, SAr, SAlk, azole, *etc.*

Compounds **346** – **348** are valuable precursors for the preparation of five-membered benzannulated heterocycles. Thus, the acid-catalyzed cyclization of *O*-(3-amino-5-nitrophenyl) ketoximes **349**, generated from TNB, affords an equimolar mixture of 6-amino-4-nitrobenzofurans **350** and 4-hydroxy-6-nitroindoles **351**[391] (Scheme 120). Some compounds **351** exhibit higher antifungal activity against different types of fungal pathogens compared to the standard fungicide triadimefon.[392]

Scheme 120

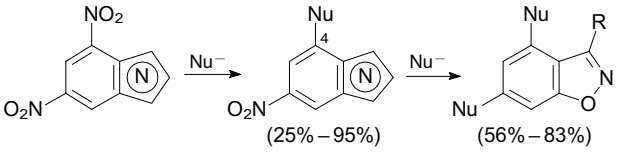


R = H, Me; Ar = Ph, 2-ClC_6H_4, 2-$MeOC_6H_4$, 4-HOC_6H_4, 2,4-$Cl_2C_6H_3$, 4-FC_6H_4

Trinitrotoluene was used to synthesize a series of five-membered benzannulated heterocycles (benzothiophenes,[393] benzo[*d*]isothiazoles,[394, 395] 2,3-dihydro-1,4-benzothiazines,[396] indoles, indazoles, 2,3-dihydrobenzofurans and so on). The transformations giving these classes of compounds include sequential or simultaneous transformations of methyl and *ortho*-nitro groups.[397] In most of the synthesized

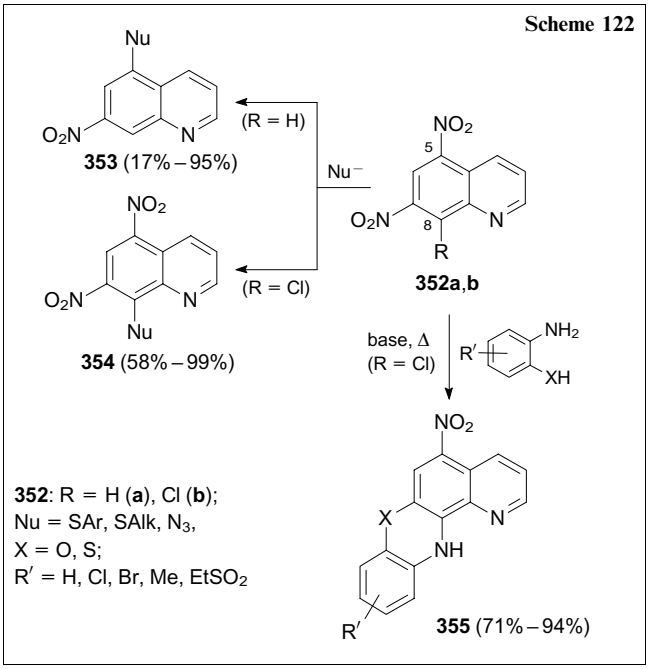
annulated systems, the nitro group at position 4 can be regioselectively replaced on treatment with anionic nucleophiles, which significantly increases the synthetic potential of the method (Scheme 121).[398–402] Generally, the replacement occurs under mild conditions; in the case of π-deficient benzo[*d*]isoxazoles, both nitro groups can be successively replaced.[403]

Scheme 121



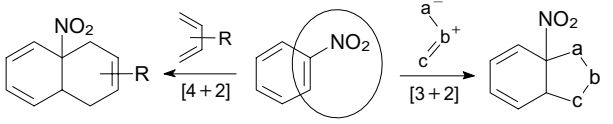
Reactions of 8-*R*-5,7-dinitroquinolines **352a**,**b** with anionic nucleophiles lead to the selective replacement of the nitro group at position 5 (R = H)[404] or the chlorine atom at position 8 (R = Cl)[405] (products **353** and **354**, respectively) (Scheme 122). The reaction of 8-chloro-5,7-dinitroquinoline **352b** with binucleophiles (*o*-aminophenols and thiophenols) was accompanied by the successive replacement of the chlorine atom and the nitro group to form pyrido[2,3-*a*]phenoxazines and phenothiazines **355**.[406] In the case of aminothiophenols, Smiles rearrangement products were isolated.

Scheme 122



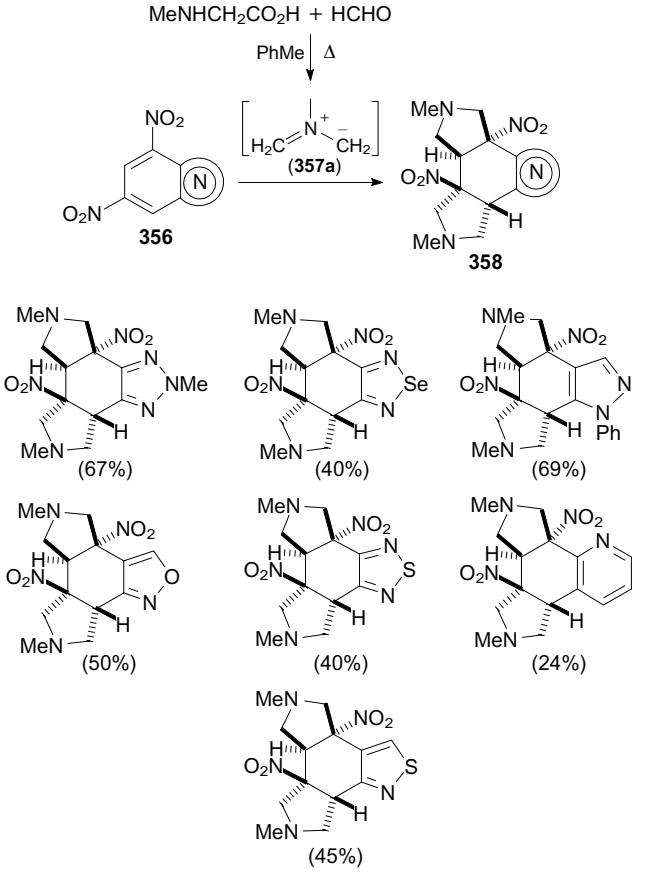
Another area of research in chemistry of aromatic nitro compounds that has emerged in the past decade is based on the ability of polynitroarenes to undergo dearomatization *via* [3 + 2]- and [4 + 2]-cycloaddition. It was found that the C=C–NO$_2$ moieties that are present in π-deficient nitroarenes can be involved in pericyclic reactions both as dienophiles and heterodienes. Besides, they can take part in addition reactions with certain dipoles to form five-membered annulated heterocycles. In terms of chemical properties, nitrovinyl moieties of nitroarenes are similar to conjugated nitroalkenes (Scheme 123).

Scheme 123



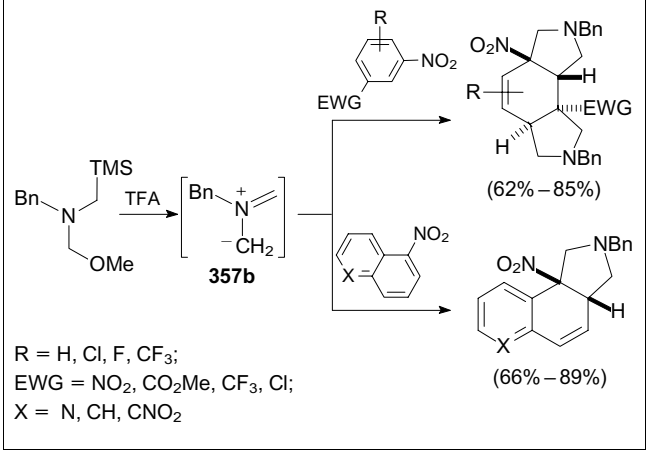
Aromatic carbocycles very rarely participate in pericyclic reactions as 2π-components, and only reactions of 4- and 5-nitrobenzofuroxans with diazoacetic esters[407] are known as the addition reactions of dipoles to nitroarenes. Shevelev and co-workers[408–410] demonstrated that *meta*-dinitrobenzenes **356** annulated with different nitrogen-containing heterocycles are readily involved in 1,3-dipolar cycloaddition reactions with *N*-methyl azomethine ylide **357a** generated *in situ* from sarcosine and paraformaldehyde (Scheme 124). The addition of two equivalents of the dipole to both nitrovinyl moieties gives the previously unknown tetracyclic systems **358**. These reactions are diastereoselective and afford *anti*-oriented heterocyclic moieties.

Scheme 124



Afterwards, Lee *et al.*[411,412] performed the reactions of *N*-benzyl azomethine ylide **357b** with mono- and dinitro derivatives of benzene, naphthalene and benzannulated heterocycles. The nitro group and an electron-withdrawing substituent at the benzene ring are required for the reaction with mononuclear aromatic compounds to proceed (mononitrobenzene is not involved in the reaction with **357b** under these conditions); in the case of naphthalene derivatives, one nitro group is enough for this reaction (Scheme 125). In the latter case, the addition of the second equivalent of the

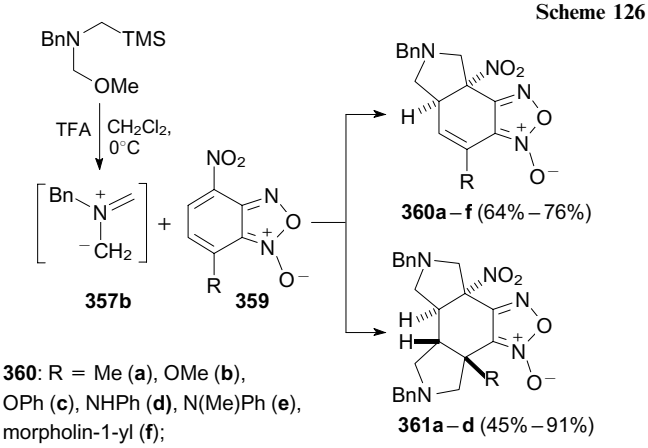
Scheme 125



dipole also occurs from the opposite side with respect to the first equivalent. The concerted mechanism of cycloaddition was proposed based on quantum chemical calculations.

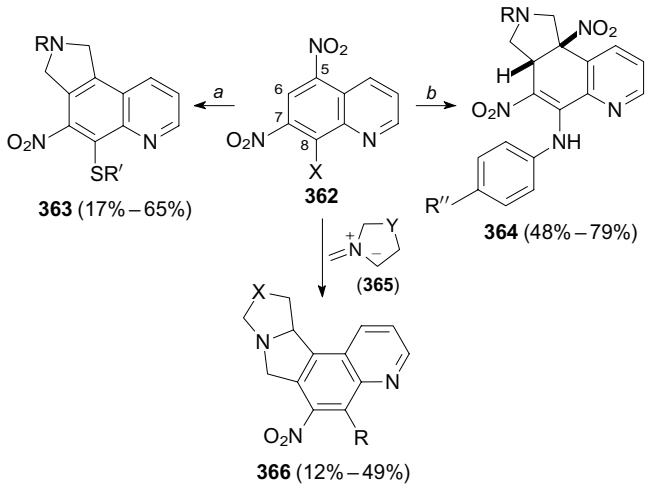
Mononitrobenzenes annulated with certain electron-deficient azoles (furazan, isoxazole, thiadiazole) react with azomethine ylides to form cycloaddition products at the nitro-activated C=C bond.[413, 414] The reaction of 7-R-4-nitrobenzofuroxans **359** with dipole **357b** affords monoadducts **360** or bis-adducts **361** depending on the nature of the substituent R (Scheme 126).[415]

Scheme 126



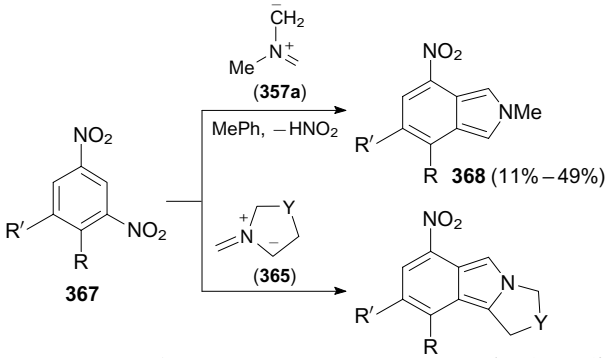
The output of the reaction with 8-substituted dinitroquinolines **362** depends on the type of the substituent C(8)–X. Thus, if X = SAlk or SAr, the cycloaddition occurs regioselectively at the C(5)–C(6) bond regardless of the structure of dipole **357** and the reaction temperature and is followed by elimination of HNO_2 and rearomatization of the benzene ring to give isoindolines **363** (Scheme 127).[405, 416] Apparently, the substituent at position 8 hinders the addition of the dipole to the C(7)–C(8) bond. The reaction of 8-arylamino-substituted dinitroquinolines (**362**, X = NHAr) with azomethine ylides **357a**,**b** affords fused pyrrolidines **364**. In these reactions, the elimination of nitrous acid does not usually occur, as opposed to 8-thio-substituted quinolines. Reactions of dinitroquinolines **362** with cyclic azomethine ylides **365a**,**b** produce polycyclic compounds **366**.

Scheme 127



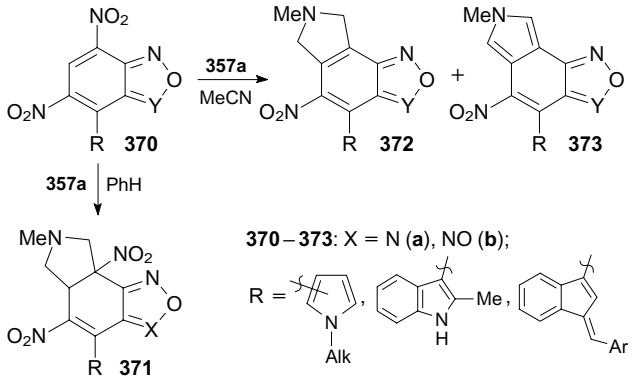
Monocyclic nitroarenes **367** (TNB, TNT and their analogues) react with dipole **357a** to form isoindoles **368** (Scheme 128).[417] It is worth noting that in this case, as opposed to the reactions of nitrobenzoazoles, the addition of the dipole is accompanied by elimination of HNO_2 resulting in rearomatization. The addition occurs selectively at positions 2 and 3 with respect to the substituent R. The use of dipoles **365** generated from cyclic amino acids (proline and thiaproline) allows the synthesis of isoindoles **369** fused to another heterocycle.

Scheme 128



Kurbatov and co-workers[418, 419] found that the output of the reaction of 7-substituted 4,6-dinitrobenzofurazans **370a** and -furoxans **370b** with azomethine ylide **357a** depends on the nature of the solvent (Scheme 129). In benzene, the reaction occurs mainly as dearomatization to form heterocyclic products **371a**,**b**. Meanwhile, compounds **372**, generated *via* the elimination of HNO_2, and their oxidation products, pyrroles **373**, were detected in the reaction performed in acetonitrile.

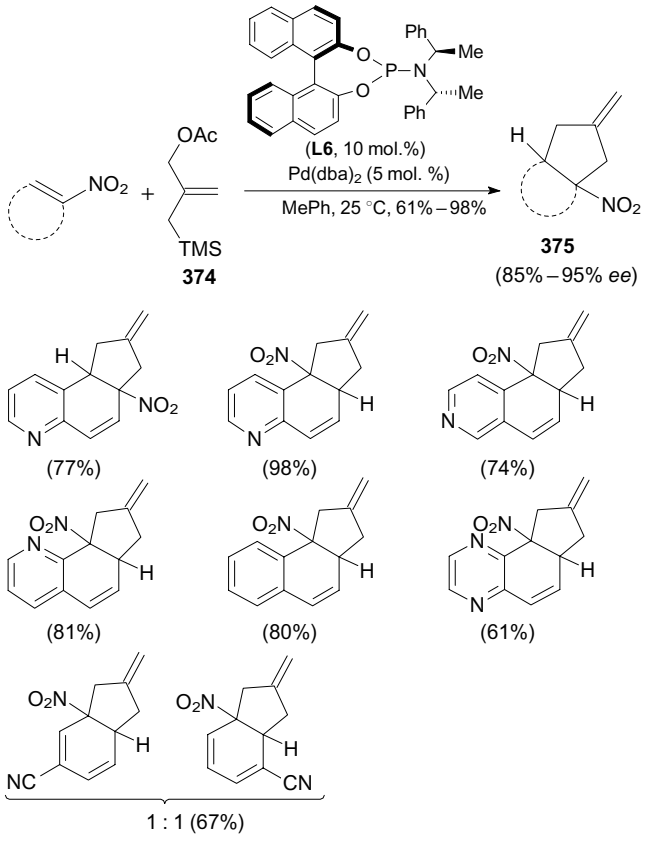
Scheme 129



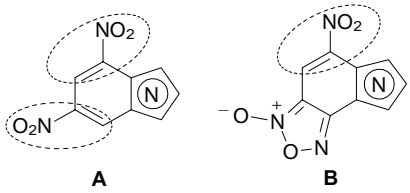
An interesting example of dearomatization of nitroarenes is the Pd-catalyzed [3 + 2]-cycloaddition of trimethylenemethane, generated from compound **374**, to nitrated benzene, naphthalene and quinoline derivatives (Scheme 130).[420] In the presence of $Pd(dba)_2$ and phosphoramidite ligands, nitroarenes undergo dearomatization and cyclopentane ring annulation. The use of chiral ligand **L6** allows the synthesis of adducts **375** with an enantiomeric purity of 85% – 95% *ee*.

The ability of strongly electrophilic aromatic polynitro compounds to participate in normal or inverse electron demand Diels – Alder reactions is equally important. Two structural types of nitroarenes are known, which are capable of forming adducts with dienes and nucleophilic dienophiles: dinitrobenzene fused to a strongly electron-withdrawing azole ring (furoxan, furazan, isoxazole, *etc.*)

Scheme 130



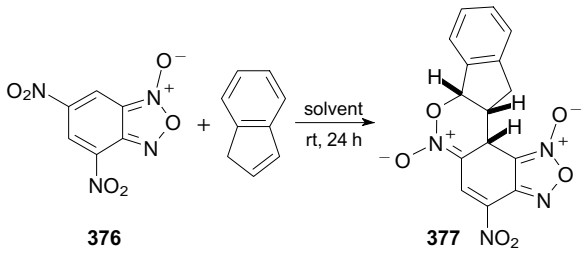
Structures A, B



and nitrobenzofuroxans annulated with π-deficient azoles or azines (structures **A** and **B**).

Terrier and co-workers[421] were the first to discover this transformation. They demonstrated that the spectroscopic characteristics of the product that was formed upon mixing of equimolar amounts of 4,6-dinitrobenzofuroxan (**376**) and indene are significantly different from those of σ-complexes of compound **376** isolated earlier. The authors concluded that the reaction affords dihydro-1,2-oxazine *N*-oxide **377** (Scheme 131). This product can be formed either in two steps (through a σ-complex) or in a concerted fashion through a cyclic transition state with inverse electron transfer.

Scheme 131



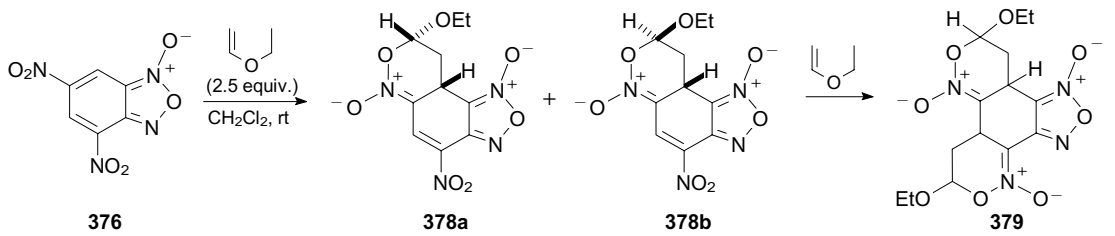
More recently, such cycloadducts were found to be generated by the reaction of **376** with other electron-donating dienophiles, in particular with ethyl vinyl ether.[422] This reaction in the presence of excess dienophile (2.5 equiv.) gave a mixtures of diastereomeric dihydro-1,2-oxazine *N*-oxides **378a** and **378a** (*dr* = 4 : 1) (Scheme 132). The reaction performed in ethyl vinyl ether afforded bis-adduct **379** (diastereomeric mixture).

The dual reactivity of 4,6-dinitrobenzofuroxan (**376**) in [4 + 2]-cycloaddition reactions was clearly demonstrated in relation to the reaction of **376** with cyclopentadiene.[423] Upon addition of the latter to a solution of **376** in chloroform at −30 °C, adducts **380a** and **380b** were initially detected (^{1}H NMR). These adducts were gradually transformed into polycyclic product **381** with increasing temperature (Scheme 133). Therefore, two competing normal and inverse electron demand reactions occur in an early step.

Other strongly electrophilic aromatic nitro compounds also participate in Diels – Alder reactions. For instance, the reaction of 4,6-dinitro-2-picrylbenzotriazole 1-oxide (**382a**) with cyclopentadiene affords related [4 + 2]-cycloaddition product **383a** containing the tetrahydrooxazine ring (92% yield) (Scheme 134).[424] 4,6-Dinitrobenzofurazan (**382b**) and 4,6-dinitrobenzothiadiazole (**382c**) exhibit a similar behaviour[425] and form bis-adducts **383b** and **383c** with cyclopentadiene in 68% and 32% yields, respectively.

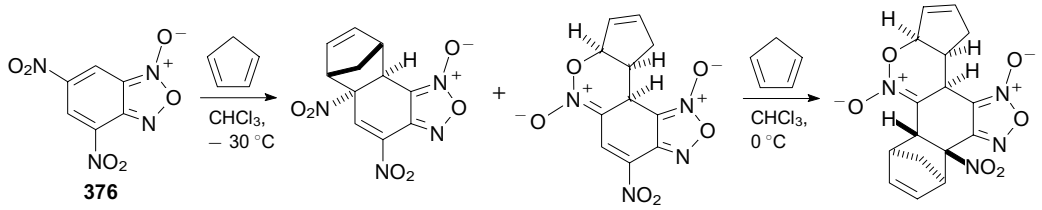
Under mild conditions, less electrophilic dinitroanthranil **384**[426] reacts as a dienophile with 1-(trimethylsilyloxy)-1,3-butadiene in $CHCl_3$ at the C(6) – C(7) bond to give cycloadduct **385** with high regio- and stereoselectivity (Scheme 135). Compound **385** reacts as heterodiene with

Scheme 132



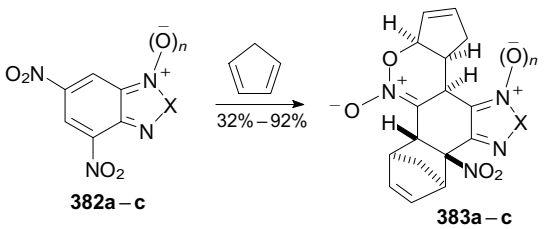
376 **378a** **378b** **379**

Scheme 133

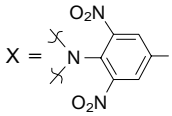


376 **380a** **380b** **381**

Scheme 134



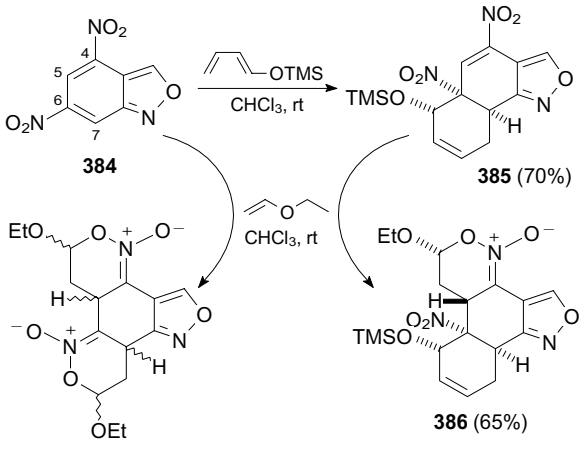
382a – c **383a – c**

X = , n = 1 (**a**); n = 0: X = O (**b**), S (**c**)

vinyl ether to form tetracyclic product **386** containing the tetrahydrooxazine ring. In the reaction of dinitroanthranil **384** with ethyl vinyl ether, both nitroalkene moieties act as heterodienes. The reaction occurs with good stereoselectivity (dr = 9 : 1) and affords bis-adduct **387** containing two tetrahydrooxazine rings.[427]

Fused 14π-electron systems, in which nitrobenzene is annulated with two π-deficient aromatic heterocycles, belong to another type of nitroarenes capable of undergoing cycloaddition. Thus, 4-nitrobenzodifuroxan **388** containing a reactive nitroalkene moiety[428] reacts with both dienes and ethyl vinyl ether to give polyfused heterocycles **389** and **390**, respectively (Scheme 136). Comprehensive theoretical and experimental studies[429] showed that the reaction of **388** with cyclopentadiene initially affords tetrahydrooxazine intermediate **391**, which is then rearranged into thermodynamically more stable product **389**.

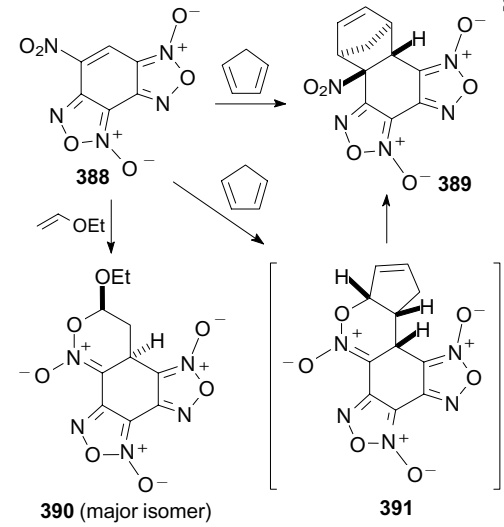
Scheme 135



384 **385** (70%) **386** (65%)

387 (47%, dr = 9 : 1)

Scheme 136

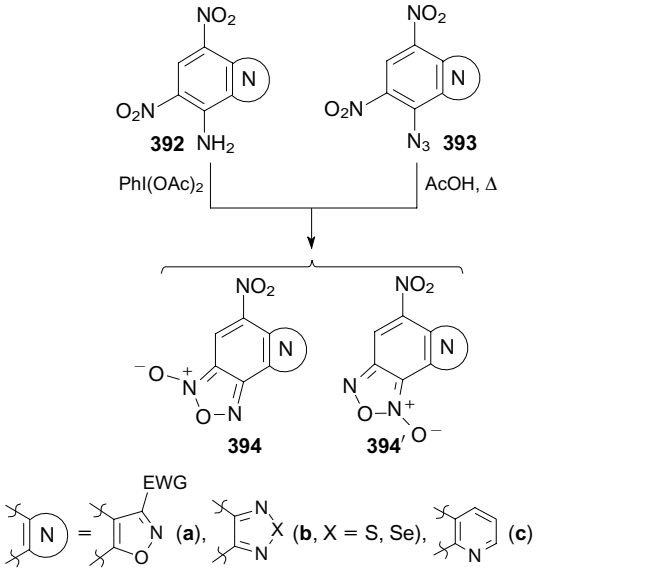


388 **389** **390** (major isomer) **391**

The superelectrophilic properties of nitroarenes are retained upon the replacement of one furoxan ring in compound **388** by another electron-deficient ring (isoxazole,[430] thiadiazole,[431] selenadiazole[410] or pyridine[416,432]). These substrates are synthesized by oxidative cyclization of aminodinitro derivatives **392** or thermolysis of dinitroazides **393** (Scheme 137). The corresponding tricyclic compounds are produced as an inseparable mixture of isomers **394** and **394′** that differ in the position of the exocyclic oxygen atom in the furoxan ring (rr = 5 : 1 – 3 : 2).

The reactions of compounds **394**/**394′** with ethyl vinyl ether afford complex heterocyclic systems **395**/**395′** containing the oxazine *N*-oxide ring, whereas the reactions with electron-donating dienes give annulated cyclohexene structures **396**/**396′** (Scheme 138). These transformations are diastereoselective, the regioisomeric ratio in the products

Scheme 137



generally being different from that in the starting substrates **394**/**394′**.

Evidently, the synthetic potential of aromatic polynitro compounds is not restricted to the above-considered reactions. The further development of strategies for dearomatization of nitroarenes may provide facile access to even more complex and synthetically valuable products and intermediates.

4. Conclusion

The reviewed data demonstrate that great progress has been achieved in recent years in the synthesis of energetic nitro compounds. New more feasible methods were developed for the production of ADN, a unique oxidant for composite solid rocket propellants. A new class of *N*-nitro compounds, nitro-*NNO*-azoxy compounds, were synthesized. These compounds are characteried by higher enthalpies of formation and a higher active oxygen content than the corresponding *N*-nitramines. Promising approaches were proposed to synthesize energetic nitrogen – oxygen systems based on nitroimides containing extended chains of nitrogen – nitrogen bonds. Simple and efficient methods were developed for the preparation of low-melting mixtures of homologues *N*,*N′*-dialkylmethylenebis(nitramines) with high plasticizing ability as promising active components of CSRPs. New high energy derivatives of polynitrogen and nitrogen – oxygen heterocycles (furazan, furoxan, pyrazole), containing several nitro groups and having high energy properties, were synthesized. Methods for the nitration of alcohols and amines (amides) in alternative solvents (liquid carbon dioxide or fluorohydrocarbons) safe for personnel and the environment were developed. These methods can be used to prepare energetic materials for different applications.

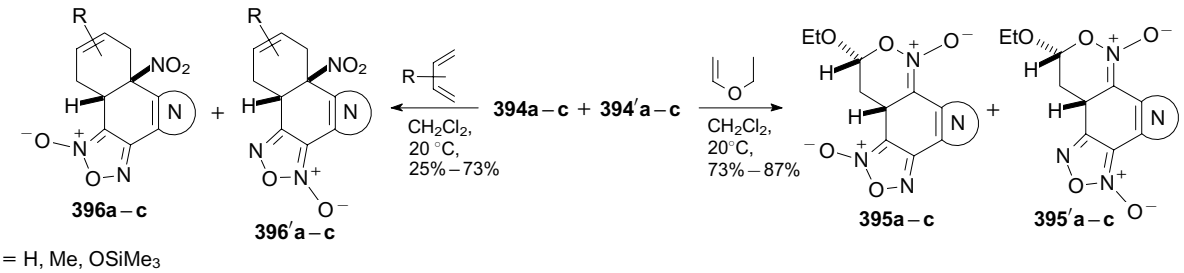
Significant progress was made in the application of nitro compounds as versatile reagents for organic synthesis. Original methods were devised for modification of aliphatic nitro compounds based on the inversion of polarity of nitroalkanes. New cycloannulation reactions of nitronates and novel methods for the regioselective functionalization of different positions in the carbon skeleton of nitroalkanes and their derivatives were developed. The stereoselective synthesis of natural products with useful biological activities and the most active enantiomers of clinically used drugs was accomplished on the basis of catalytic asymmetric reactions of nitroolefins with carbo- and heteronucleophiles. Efficient protocols were created for chemical utilization of expired TNT by its conversions into other valuable substances such as monomers, vulcanizing agents, new benzannulated heterocycles serving as core structures for the production of promising drugs.

Further progress in chemistry of nitro compounds would be expected to bring new, even more interesting results. For instance, it can be expected that potential energetic components will be produced in the series of nitro derivatives of 1,2,3,4-tetrazine 1,3-dioxide, a new class of nitrogen – oxygen heterocycles synthesized in the ZIOC RAS.[433, 434] High-density stable structures insensitive to mechanical stimuli can be designed [435, 436] and pyrazole nitro derivatives,[437, 438] in particular, those annulated with other polynitrogen heterocycles.[439, 440] The development of flow processes for continuous production of nitro compounds, including those in non-flammable liquefied gases which are characterized by reduced environmental impacts and explosion danger.[169, 441]

Further investigations of ANCs will be partly related to transformations of nitroalkanes and nitronic acid esters into drug precursors under the action of Brønsted acids [442] and transition metal compounds.[443] A particularly promising trend is the design of simple and efficient, primarily catalytic, methods of asymmetric synthesis of the most active drug enantiomers starting from available nitroalkanes and nitroolefins.[19] Approaches based on the dearomatization of polynitroaromatic compounds, in particular TNT derivatives, *via* cycloaddition and the recently developed procedures for heterocyclization of alkenes with tetranitromethane [444, 445] may provide new routes to pharmacologically valuable heterocyclic systems.

There is no doubt that due to availability, variability of physicochemical properties,[446] the ability to accumulate and, under particular conditions, release considerable amounts of chemical energy, and also a unique diversity of

Scheme 138



R = H, Me, $OSiMe_3$

useful transformations, nitro compounds will be employed as dual-use industrial products and popular reagents for organic synthesis in a long future.

References

1. E.Yu.Orlova. *Chemistry and Technology of High Energy Explosive Substances*. (Leningrad: Khimia, 1973)
2. T.Urbanski. *Chemistry and Technology of Explosives*. Vol. 4. (Oxford: Pergamon Press, 1984)
3. O.A.Luk'yanov, V.A.Tartakovsky. *Zh. Ros. Khim. O-va im. D.I.Mendeleeva,* **41** (2), 5 (1997)
4. A.H.Ghee, G.Santhosh. In *Advances in Energetic Dinitroamides*. (Singapore: World Scientific Publishing Co, 2007). P. 168
5. J.P.Agrawal, R.D.Hodgson. *Organic Chemistry of Explosives*. (England: Wiley, 2007)
6. S.S.Novikov, G.A.Shvekhgeimer, V.V.Sevost'yanova, V.A.Shlyapochnikov. *Khimiya Alifaticheskikh i Alitsiklicheskikh Nitrosoedinenii*. (Chemistry of Aliphatic and Alicyclic Nitro Compounds). (Moscow: Khimiya, 1974)
7. L.I.Khmel'nitskii, T.I.Godovikova, S.S.Novikov. *Khimiya Furoksanov. Reaktsii i Primenenie*. (Chemistry of Furoxans. Reactions and Application). (Moscow: Nauka, 1996)
8. S.L.Ioffe, V.A.Tartakovskii, S.S.Novikov. *Russ. Chem. Rev.*, **35**, 19 (1966)
9. A.M.Tafesh, J.Weiguny. *Chem. Rev.*, **96**, 2035 (1996)
10. H.Goksu, H.Sert, B.Kilbas, F.Sen. *Curr. Org. Chem.*, **21**, 794 (2017)
11. R.Ballini, M.Petrini. *Adv. Synth. Catal.*, **357**, 2371 (2015)
12. C.Palomo, M.Oiarbide, A.Laso. *Eur. J. Org. Chem.*, 2561 (2007)
13. A.M.Faísca Phillips. *Curr. Org. Synth.*, **13**, 687 (2016)
14. V.V.Perekalin, E.S.Lipina, V.M.Berestovitskaya, D.A.Efremov. *Nitroalkenes. Conjugated Nitrocompounds*. (London: Wiley, 1994)
15. V.A.Tartakovskii, I.E.Chlenov, S.S.Smagin, S.S.Novikov. *Bull. Acad. Sci. USSR, Div. Chem. Sci.*, **13**, 549 (1964)
16. S.L.Ioffe, M.V.Kashutina, V.M.Shitkin, A.Z.Jankelevich, A.A.Levin, V.A.Tartakovskii. *Bull. Acad. Sci. USSR, Div. Chem. Sci.*, **21**, 1292 (1972)
17. S.E.Denmark, J.J.Cottell. In *Synthetic Applications of 1,3-Dipolar Cycloaddition Chemistry Toward Heterocycles and Natural Products*. (Eds A.Padwa, W.H.Pearson). (Hoboken, NJ: Wiley, 2003). P. 83
18. R.Y.Baiazitov, S.E.Denmark. In *Methods and Applications of Cycloaddition Reactions in Organic Syntheses*. (Ed. N.Nishiwaki). (Wiley, 2014). P. 471
19. A.Yu.Sukhorukov, A.A.Sukhanova, S.G.Zlotin. *Tetrahedron*, **72**, 6191 (2016)
20. M.Reardon, E.Bender. *J. Forensic Sci.*, **50**, 1 (2005)
21. R.Meyer, J.Kohler, A.Homburg. *Explosives*. (Weinheim: Wiley-VCH, 2016)
22. Patent US 5693794 (1988)
23. A.T.Nielsen, A.P.Chafin, S.L.Christian, D.W.Moore, M.P.Nadler, R.A.Nissan, D.J.Vanderah, R.D.Gilardi, C.F.George, J.L.Flippen-Anderson. *Tetrahedron*, **54**, 11793 (1998)
24. O.A.Luk'yanov, V.P.Gorelik, V.A.Tartakovskii. *Russ. Chem. Bull., Int. Ed.*, **43**, 89 (1994)
25. O.A.Luk'yanov, Y.V.Konnova, T.A.Klimova, V.A.Tartakovsky. *Russ. Chem. Bull., Int. Ed.*, **43**, 1200 (1994)
26. O.A.Luk'yanov, O.V.Anikin, V.P.Gorelik, V.A.Tartakovsky. *Russ. Chem. Bull., Int. Ed.*, **43**, 1457 (1994)
27. V.A.Shlyapochnikov, N.O.Cherskaya, O.A.Luk'yanov, V.P.Gorelik, V.A.Tartakovsky. *Russ. Chem. Bull., Int. Ed.*, **43**, 1522 (1994)
28. O.A.Luk'yanov, N.I.Shlykova, V.A.Tartakovsky. *Russ. Chem. Bull., Int. Ed.*, **43**, 1680 (1994)
29. O.A.Luk'yanov, A.R.Agevnin, A.A.Leichenko, N.M.Seregina, V.A.Tartakovsky. *Russ. Chem. Bull., Int. Ed.*, **44**, 108 (1995)
30. V.A.Shlyapochnikov, G.I.Oleneva, N.O.Cherskaya, O.A.Luk'yanov, V.P.Gorelik, O.V.Anikin, V.A.Tartakovsky. *Russ. Chem. Bull., Int. Ed.*, **44**, 1449 (1995)
31. H.Östmark, U.Bemm, H.Bergman, A.Langlet. *Thermochim. Acta*384, 253 (2002)
32. Patent US 5316749A (1994)
33. Patent US 5976483A (1999)
34. J.C.Bottaro, P.E.Penwell, R.J.Schmitt. *J. Am. Chem. Soc.*, **119**, 9405 (1997)
35. J.Epsztajn, A.R.Katritzky. *Tetrahedron Lett.*, **10**, 4739 (1969)
36. J.Epsztajn, E.Lunt, A.R.Katritzky. *Tetrahedron*, **26**, 1665 (1970)
37. A.R.Katritzky, J.W.Mitchell. *J. Chem. Soc., Perkin Trans. 1*, 2624 (1973)
38. O.P.Shitov, V.A.Vyazkov, V.A.Tartakovskii. *Bull. Acad. Sci. USSR, Div. Chem. Sci.*, **38**, 2440 (1989)
39. T.M.Klapötke, C.Petermayer, D.G.Piercey, J.Stierstorfer. *J. Am. Chem. Soc.*, **134**, 20827 (2012)
40. V.A.Myasnikov, V.A.Vyazkov, I.L.Yudin, O.P.Shitov, V.A.Tartakovskii. *Bull. Acad. Sci. USSR, Div. Chem. Sci.*, **40**, 1116 (1991)
41. A.I.Glushkov, O.P.Shitov, V.A.Tartakovsky. *Russ. Chem. Bull., Int. Ed.*, **50**, 2481 (2001)
42. A.I.Glushkov, O.P.Shitov, V.A.Tartakovsky. *Russ. Chem. Bull., Int. Ed.*, **52**, 467 (2003)
43. K.I.Rezchikova, A.M.Churakov, V.A.Shlyapochnikov, V.A.Tartakovskii. *Mendeleev Commun.*, **4**, 100 (1994)
44. K.I.Rezchikova, V.A. Shlyapochnikov, V.A.Tartakovsky. *Russ. Chem. Bull., Int. Ed.*, **43**, 1676 (1994)
45. A.M.Churakov, S.L.Ioffe, V.A.Tartakovskii. *Mendeleev Commun.*, **6**, 20 (1996)
46. A.M.Churakov, S.E.Semenov, S.L.Ioffe, Yu.A.Strelenko, V.A.Tartakovsky. *Russ. Chem. Bull., Int. Ed.*, **46**, 1042 (1997)
47. N.E.Leonov, M.S.Klenov, O.V.Anikin, A.M.Churakov, Yu.A.Strelenko, K.A.Monogarov, V.A.Tartakovsky. *Eur. J. Org. Chem.*, 91 (2019)
48. O.V.Anikin, N.E.Leonov, M.S.Klenov, A.M.Churakov, A.A.Voronin, A.A.Guskov, N.V.Muravyev, Yu.A.Strelenko, I.V.Fedyanin, V.A.Tartakovsky. *Eur. J. Org. Chem.*, 4189 (2019)
49. H.Li, B.Z.Wang, X.Z.Li, J.F.Tong, W.P.Lai, X.Z.Fan. *Bull. Korean Chem. Soc.*, **34**, 686 (2013)
50. A.B.Sheremetev, S.E.Semenov, V.S.Kuzmin, Yu.A.Strelenko, S.L.Ioffe. *Chem. – Eur. J.*, **4**, 1023 (1998)
51. D.Spitzer, B.Wanders, M.R.Schäfer, R.Welter. *J. Mol. Struct.*, **644**, 37, (2003)
52. V.A.Tartakovskii, A.S.Ermakov, V.A.Koroban, F.R.Alimov, N.V.Sigai. *Russ. Chem. Bull. Int. Ed.*, **42**, 1916 (1993)
53. R.Vijayalakshmi, N.H.Naik, G.M.Gore, A.K.Sikder. *J. Energ. Mater.*, **33**, 1, (2015)
54. Technical Report P.B. 925, D.A.G., Krümmel, Düneberg, Christianstadt. US Deparment of Commerce, Washington (1945)
55. W.P.Binnie, H.L.Cohen, G.F.Wright. *J. Am. Chem. Soc.*, **72**, 4457 (1950)
56. A.H.Dinwoodie, J.A.Gibson, J.B.Parker. *J. Chem. Soc. (C)*, 496 (1967)
57. V.A.Tartakovsky, A.S.Ermakov, D.B.Vinogradov, N.V.Sigai. *Russ. Chem. Bull. Int. Ed.*, **46**, 1024 (1997)
58. V.A.Tartakovsky, A.S.Ermakov, N.V.Sigai, D.B.Vinogradov. *Russ. Chem. Bull. Int. Ed.*, **49**, 1082 (2000)
59. V.A.Tartakovsky, A.S.Ermakov, N.V.Sigai, O.N.Varfolomeeva. *Russ. Chem. Bull., Int. Ed.*, 1079 (2000)
60. V.A.Tartakovskii, A.S.Ermakov, N.V.Sigai, S.A.Serkov. *Russ. J. Org. Chem.*, **42**, 949 (2006)

61. N.V.Sigai, S.A.Serkov, A.S.Ermakov, V.A.Tartakovskii, O.A.Luk'yanov, T.V.Ternikova. *Russ. J. Org. Chem.*, **43**, 458 (2007)
62. V.A.Tartakovsky, A.S.Ermakov, D.B.Vinogradov, P.V.Bulatov. *Russ. Chem. Bull., Int. Ed.*, **47**, 652 (1998)
63. V.A.Ostrovskii, M.S.Pevzner, T.P.Kofman, M.B.Shcherbinin, I.V.Tselinskii. In *Targets in Heterocyclic Systems*. Vol. 3. (Eds O.A.Attanasi, D. Spinelli). (Italian Society of Chemistry, 1999). P. 467
64. V.A.Ostrovskii, G.I.Koldobskii and R.E.Trifonov. In *Comprehensive Heterocyclic Chemistry III*. Vol. 6. (Eds A.R.Katrizky, C.A.Ramsden, E.F.V.Scriven, R.J.K.Taylor). (Oxford: Elsevier, 2008). P. 257
65. R.A.Olofson, J.S.Michelman. *J. Org. Chem.*, **30**, 1854 (1965)
66. A.B.Sheremetev, N.N.Makhova, W.Friedrichsen. *Adv. Heterocycl. Chem.*, **78**, 65 (2001)
67. N.N.Makhova, A.S.Kulikov. *Russ. Chem. Rev.*, **82**, 1007 (2013)
68. H.Z.Li, J.S.Li, M.Huang, X.Q.Zhou. *Chin. J. Org. Chem.*, **29**, 798 (2009)
69. A.B.Sheremetev, V.O.Kulagina, N.S.Aleksandrova, D.E.Dmitriev, Y.A.Strelenko, V.P.Lebedev, Yu.N.Matyushin. *Propell. Explos. Pyrotech.*, **23**, 142 (1998)
70. T.S.Novikova, T.M.Melnikova, O.V.Kharitonova, V.O.Kulagina, N.S.Aleksandrova, A.B.Sheremetev, T.S.Pivina, L.I.Khmelnitskii, S.S.Novikov. *Mendeleev Commun.*, **4**, 138 (1994)
71. T.S.Pivina, D.V.Sukhachev, A.V.Evtushenko, L.I.Khmelnitsky. *Propel. Explos. Pyrothech.*, **20**, 5 (1995)
72. A.Gunasekaran, J.H.Boyer. *Heteroatom Chem.*, **4**, 521 (1993)
73. M.D.Coburn. *J. Labelled Compds. Radiopharm.*, **22**, 183 (1985)
74. A.B.Sheremetev, O.V.Kharitonova, T.M.Mel'nikova, T.S.Novikova, V.S.Kuz'min, L.I.Khmel'nitskii. *Mendeleev Commun.*, **6**, 141 (1996)
75. V.O.Kulagina, T.S.Novikova, T.M.Mel'nikova, L.I.Khmel'nitskii. *Chem. Heterocycl. Comp.*, **30**, 631 (1994)
76. A.Gunasekaran, M.L.Trudell, J.H.Boyer. *Heteroatom. Chem.*, **5**, 441 (1994)
77. A.M.Churakov, S.E.Semenov, S.L.Ioffe, Yu.A.Strelenko, V.A.Tartakovskii. *Mendeleev Commun.*, **5**, 102 (1995)
78. D.B.Lempert, A.B.Sheremetev. *Chem. Heterocycl. Compd.*, **52**, 1070 (2016)
79. Q.Yu, G.Cheng, X.Ju, C.Lu, Q.Lin, H.Yang. *Dalton Trans.*, **46**, 14301 (2017)
80. P.F.Pagoria, M.-X.Zhang, N.B.Zuckerman, A.J.DeHope, D.A.Parrish. *Chem. Heterocycl. Compd.*, **53**, 760 (2017)
81. N.N.Makhova, I.V.Ovchinnikov, A.S.Kulikov, D.V.Khakimov, M.S.Molchanova, T.S.Pivina. *Propell. Explos. Pyrotech.*, **37**, 549 (2012)
82. T.I.Godovikova, O.A. Rakitin, S.P.Golova, S.A.Vozchikova, L.I.Khmel'nitskii. *Mendeleev Commun.*, **3**, 209 (1993)
83. I.V.Ovchinnikov, N.N.Makhova, L.I.Khmel'nitskii. *Mendeleev Commun.*, **3**, 210 (1993)
84. I.V.Ovchinnikov, N.N.Makhova, L.I.Khmel'nitskii, V.S.Kuz'min, L.N.Akimova, V.I.Pepekin. *Dokl. Chem.*, **359**, 67 (1998)
85. T.Guo, M.Liu, X-C.Huang, Z.-j.Wang, S.-j.Qiu, Z.-x.Ge, Z.-h.Meng. *J. Analyt. Appl. Pyrolysis*, **128**, 451 (2017)
86. D.Fischer, T.M.Klapötke, J.Stierstorfer. *Eur. J. Inorg. Chem.*, 5808 (2014)
87. C.He, H.Gao, G.H.Imler, D.A.Parrish, J.M.Shreeve. *J. Mater. Chem. A*, **6**, 9391 (2018)
88. L.L.Fershtat, M.I.Struchkova, A.S.Goloveshkin, I.S.Bushmarinov, N.N.Makhova. *Heteroatom. Chem.*, **25**, 226 (2014)
89. R.Matsubara, A.Ando, Yu.Saeki, K.Eda, N.Asada, T. Tsutsumi, Y.S.Shin, M.Hayashi. *J. Heterocycl. Chem.*, **53**, 1094 (2016)
90. A.Kunai, T.Doi, T.Nagaoka, H.Yagi, K.Sasaki. *Bull. Chem. Soc. Jpn.*, **63**, 1843 (1990)
91. I.V.Ovchinnikov, A.O.Finogenov, M.A.Epishina, A.S.Kulikov, Yu.A.Strelenko, N.N.Makhova. *Russ. Chem. Bull., Int. Ed.*, **58**, 2137 (2009)
92. I.V.Ovchinnikov, A.O.Finogenov, M.A.Epishina, Yu.A.Strelenko, N.N.Makhova. *Mendeleev Commun.*, **19**, 217 (2009)
93. L.L.Fershtat, M.A.Epishina, I.V.Ovchinnikov, M.I.Struchkova, A.A.Romanova, I.V.Ananyev, N.N.Makhova. *Tetrahedron Lett.*, **57**, 5685 (2016)
94. L.L.Fershtat, A.A.Larin, M.A.Epishina, A.S.Kulikov, I.V.Ovchinnikov, I.V.Ananiyev, N.N.Makhova. *Tetrahedron Lett.*, **57**, 4268 (2016)
95. L.L.Fershtat, I.V.Ovchinnikov, M.A.Epishina, A.A.Romanova, D.B.Lempert, N.V.Muravyev, N.N.Makhova. *ChemPlusChem*, **82**, 1315 (2017)
96. A.A.Astrat'ev, D.V.Dashko, A.I.Stepanov. *Cent. Eur. J. Chem.*, **10**, 1087 (2012)
97. R.Tsyshevsky, P.F.Pagoria, M.X.Zhang, A.Racoveanu, A.D.DeHope, D.A.Parrish, M.M.Kuklja. *J. Phys. Chem., C*, **119**, 3509 (2015)
98. J.Wang, J.Li, Q.Liang, Y.Huang, H.Dong. *Propell. Explos. Pyrotech.*, **33**, 347 (2008)
99. X.Ren, S.Heng, Y.Shao, Z.Liu, G.Znag, X.Wang, F.Han. *Chin. J. Energ. Mater.*, **17**, 455 (2009)
100. C.H.Lim,T.K.Kim, K.H.Kim, K.-H.Chung, J.S.Kim. *Bull. Korean Chem. Soc.*, **31**, 1400 (2010)
101. A.I.Stepanov, D.V.Dashko, A.A.Astrat'ev. *Cent. Eur. J. Energ. Mater.*, **9**, 329 (2012)
102. T.K.Kim, J.H.Choe, B.W.Lee, K.-H.Chung. *Bull. Korean Chem. Soc.*, **33**, 2765 (2012)
103. H.Gao, J.M.Shreeve. *Chem. Rev.*, **111**, 7377 (2011)
104. P.Yin, Q.Zhang, J.M.Shreeve. *Acc. Chem. Res.*, **49**, 4 (2016)
105. P.Yin, J.M.Shreeve. *Adv. Heterocycl. Chem.*, **121**, 89 (2017)
106. A.A.Zaitsev, I.L.Dalinger, S.A.Shevelev. *Russ. Chem. Rev.*, **78**, 589 (2009)
107. I.L.Dalinger, T.K.Shkinyova, S.A.Shevelev, V.S.Kuz'min, E.A.Arnautova, T.S.Pivina. In *Proceedings of the 29th International Annual Conference of ICT*. (Karlsruhe, FRG, 1998) P. 57-1
108. K.V.Domasevitch, I.Gospodinov, H.Krautscheid, T.M.Klapötke, J.Stierstorfer. *New J. Chem.*, **43**, 1305 (2019)
109. S.A.Shevelev, I.L.Dalinger, T.K.Shkineva, B.I.Ugrak. *Russ. Chem. Bull.*, **42**, 1857 (1993)
110. A.B.Sheremetev, I.L.Yudin, N.V.Palysaeva, K.Yu.Suponitsky. *J. Heterocycl. Chem.*, **49**, 394 (2012)
111. T.K.Shkineva, A.V.Kormanov, V.N.Boldinova, I.A.Vatsadze, I.L.Dalinger. *Chem. Heterocycl. Compd.*, **54**, 703 (2018)
112. Y.Tang, D.Kumar, J.M.Shreeve. *J. Am. Chem. Soc.*, **139**, 13684 (2017)
113. D.Kumar, Y.Tang, C.He, G.H.Imler, D.A.Parrish, J.M.Shreeve. *Chem. – Eur. J.*, **24**, 17220 (2018)
114. I.L.Dalinger, I.A.Vatsadze, T.K.Shkineva, A.V.Kormanov, A.M.Kozeev, B.B.Averkiev, A.I.Dalinger, M.K.Beklemishev, A.B.Sheremetev. *Chem. Heterocycl. Compd.*, **51**, 545 (2015)
115. S.A.Shevelev, I.L.Dalinger, T.K.Shkineva, B.I.Ugrak, V.I.Gulevskaya, M.I.Kanishchev. *Russ. Chem. Bull.*, **42**, 1063 (1993)
116. J.Zhang, D.A.Parrish, J.M.Shreeve. *Chem. – Asian. J.*, **9**, 2953 (2014)
117. Y.Li, Y.Shu, B.Wang, S.Zhang, L.Zhai. *RSC Adv.*, **6**, 84760 (2016)
118. J.Zhang, P.Yin, L.A.Mitchell, D.A.Parrish, J.M.Shreeve. *J. Mater. Chem. A*, **4**, 7430 (2016)
119. P.Yin, J.H.Zhang, L.A.Mitchell, D.A.Parrish, J.M.Shreeve. *Angew. Chem., Int. Ed.*, **55**, 12895 (2016)
120. I.L.Dalinger, N.I.Zubanova, V.S. Kuz'min, S.A.Shevelev. *Russ. Chem. Bull.*, **42**, 1211 (1993)
121. V.M.Vinogradov, T.I.Cherkasova, I.L.Dalinger, S.A.Shevelev. *Russ. Chem. Bull.*, **42**, 1552 (1993)

122. S.A.Shevelev, V.M.Vinogradov, I.L.Dalinger, T.I.Cherkasova. *Russ. Chem. Bull.*, **42**, 1861 (1993)
123. I.L.Dalinger, I.A.Vatsadze, T.K.Shkineva, G.P.Popova, B.I.Ugrak, S.A.Shevelev. *Russ. Chem. Bull.*, **59**, 1631 (2010)
124. A.V.Kormanov, D.L.Lipilin, T.K.Shkineva, I.A.Vatsadze, A.M.Kozeev, I.L.Dalinger. *Chem. Heterocycl. Compd.*, **53**, 876 (2017)
125. I.L.Dalinger, T.I.Cherkasova, G.P.Popova, T.K.Shkineva, I.A.Vatsadze, S.A.Shevelev, M.I.Kanishchev. *Russ. Chem. Bull., Int. Ed.*, **58**, 410 (2009)
126. M.C.Schulze, B.L.Scott, D.E.Chavez. *J. Mater. Chem. A.*, **3**, 17963 (2015)
127. J.R.D.Schmidt, G.S.Lee, P.F.Pagoria, A.R.Mitchell, R.Gilardi. *J. Heterocycl. Chem.*, **38**, 1227 (2001)
128. S.Ek, N.V.Latypov. *J. Heterocycl. Chem.*, **51**, 1621 (2014)
129. Y.L.Wang, F.-Q. Zhao, Y.-P.Ji, Q.Pan, J.-H.Yi, T.An, W.Wang. *J. Analyt. Appl. Pyrol.*, **98**, 231 (2012)
130. M.Zhang, W.Fu, C.Li, H.Gao, L.Tang, Z.Zhou. *Eur. J. Inorg. Chem.*, 2883 (2017)
131. I.L.Dalinger, G.P.Popova, I.A.Vatsadze, T.K.Shkineva, S.A.Shevelev. *Russ. Chem. Bull., Int. Ed.*, **58**, 2185 (2009)
132. G.Herve, C.Roussel, H.Graindorge. *Angew. Chem., Int. Ed.*, **49**, 3177 (2010)
133. Y.Zhang, Y.Guo, Y.-H.Joo, D.A.Parrish, J.M.Shreeve. *Chem. – Eur. J.*, **16**, 10778 (2010)
134. I.L.Dalinger, I.A.Vatsadze, T.K.Shkineva, G.P.Popova, S.A.Shevelev. *Mendeleev Commun.*, **20**, 253 (2010)
135. I.L.Dalinger, A.V.Kormanov, I.A.Vatsadze, O.V.Serushkina, T.K.Shkineva, K.Yu.Suponitsky, A.N. Pivkina, A.B.Sheremetev. *Chem. Heterocycl. Compd.*, **52**, 1025 (2016)
136. Y.Tang, Y.Lin, G.H.Imler, D.A.Parrish, J.M.Shreeve. *Org. Lett.*, **21**, 2610 (2019)
137. I.L.Dalinger, T.I.Cherkasova, S.A.Shevelev. *Mendeleev Commun.*, **7**, 58 (1997)
138. M.-X.Zhang, P.F.Pagoria, G.H.Imler, D.A.Parrish. *J. Heterocycl. Chem.*, **56**, 781 (2019)
139. Y.Du, J.Zhang, P.Peng, H.Su, S.Li, S.Pang. *New J. Chem.*, **41**, 9244 (2017)
140. Y.Tang, C.He, G.H.Imler, D.A.Parrish, J.M.Shreeve. *Chem. Commun.*, **54**, 10566 (2018)
141. Y.Tang, C.He, G.H.Imler, D.A.Parrish, J.M.Shreeve. *ACS Appl. Energy Mater.*, **2**, 2263 (2019)
142. V.M.Vinogradov, I.L.Dalinger, S.A.Shevelev. *Mendeleev Commun.*, **3**, 111 (1993)
143. I.L.Dalinger, A.V.Kormanov, I.A.Vatsadze, T.K.Shkineva, A.M.Kozeev, B.B.Averkiev, A.B.Sheremetev. *Chem. Heterocycl. Compd.*, **51**, 819 (2015)
144. P.Yin, D.A.Parrish, J.M.Shreeve. *J. Am. Chem. Soc.*, **137**, 4778 (2015)
145. T.K.Shkineva, I.L.Dalinger, I.A.Vatsadze, A.V.Kormanov, S.A.Shevelev. *Russ. Chem. Bull.*, **61**, 467 (2012)
146. A.V.Kormanov, T.K.Shkineva, I.A.Vatsadze, S.A.Shevelev, I.L.Dalinger. *Russ. Chem. Bull.*, **63**, 435 (2014)
147. C.He, J.Zhang, D.A.Parrish, J.M.Shreeve. *J. Mater. Chem. A*, **1**, 2863 (2013)
148. P.Yin, J.Zhang, C.He, D.A.Parrish, J.M.Shreeve. *J. Mater. Chem. A*, **2**, 3200 (2014)
149. P.Yin, D.A.Parrish, J.M.Shreeve. *Chem. – Eur. J.*, **20**, 6707 (2014)
150. V.M.Vinogradov, I.L.Dalinger, B.I.Ugrak, S.A.Shevelev. *Mendeleev. Commun.*, **6**, 139 (1996)
151. M.F.Bölter, T.M.Klapötke, T.Kustermann, T.Lenz, J.Stierstorfer. *Eur. J. Inorg. Chem.*, 4125 (2018)
152. Y.Zhang, D.A.Parrish, J.M.Shreeve. *J. Mater. Chem.*, **22**, 12659 (2012)
153. I.L.Dalinger, T.K.Shkineva, I.A.Vatsadze, G.P.Popova, S.A.Shevelev. *Mendeleev Commun.*, **21**, 48 (2011)
154. I.L.Dalinger, V.M.Vinogradov, S.A.Shevelev, V.S.Kuz'min. *Mendeleev Commun.*, **6**, 13 (1996)
155. I.L.Dalinger, A.Kh.Shakhnes, K.A.Monogarov, K.Yu.Suponitsky, A.B.Sheremetev. *Mendeleev Commun.*, **25**, 429 (2015)
156. V.V.Semenov, S.A.Shevelev, A.B.Bruskin, M.I.Kanishchev, A.T.Baryshnikov. *Russ. Chem. Bull.*, **58**, 2077 (2009)
157. X.X.Zhao, S.H.Li, Y.Wang, Y.C.Li, F.Q.Zhao, S.P.Pang. *J. Mater. Chem. A*, **4**, 5495 (2016)
158. I.L.Dalinger, A.V.Kormanov, K.Yu.Suponitsky, N.V.Muravyev, A.B.Sheremetev. *Chem. – Asian J.*, **13**, 1165 (2018)
159. V.V.Semenov, S.A.Shevelev. *Mendeleev Commun.*, **20**, 332 (2010)
160. I.L.Dalinger, I.A.Vatsadze, T.K.Shkineva, A.V.Kormanov, M.I.Struchkova, K.Yu.Suponitsky, A.A.Bragin, K.A.Monogarov, V.P.Sinditskii, A.B.Sheremetev. *Chem. – Asian J.*, **10**, 1987 (2015)
161. I.L.Dalinger, K.Yu.Suponitsky, A.N.Pivkina, A.B.Sheremetev. *Propellants Explos. Pyrotech.*, **41**, 789 (2016)
162. Y.Tang, C.He, G.H.Imler, D.A.Parrish, J.M.Shreeve. *J. Mater. Chem. A*, **6**, 5136 (2018)
163. I.L.Dalinger, K.Yu.Suponitsky, T.K.Shkineva, D.B.Lempert, A.B.Sheremetev. *J. Mater. Chem. A*, **6**, 14780 (2018)
164. *Green Energetic Materials*. (Ed. T. Brinck). (Wiley, England, 2014)
165. *Defense Industries: Science and Technology Related to Security: Impact of Conventional Munitions on Environment and Population* (Eds P.C.Branco, H.Schubert, J.Campos). (Dordrecht, Netherlands: Kluwer Academic Publishers, 2007)
166. G.Steinhauser, T.M. Klapötke. *Angew. Chem., Int. Ed.*, **47**, 3330 (2008)
167. R.P.Singh, R.D.Verma, D.T.Meshri, J.M.Shreeve. *Angew. Chem., Int. Ed.*, **45**, 3584 (2006)
168. T.M.Klapötke. In *Chemistry of High-Energy Materials*. (3rd Ed.). (Berlin: Walter de Gruyter, 2015). P. 333
169. I.V.Kuchurov, M.N.Zharkov, L.L.Fershtat, N.N.Makhova, S.G.Zlotin. *ChemSusChem*, **10**, 3914 (2017)
170. G.Cheng, X.Li, X.Qi, C.Lu. *J. Energ. Mater.*, **28**, 35 (2010)
171. H.Z.Zhi, J.Luo, G.An Feng, C.X.Lv. *Chin. Chem. Lett.*, **20**, 379 (2009)
172. X.-B.Liu, M.Lu. *E-J. Chem.*, **8**, 97 (2011)
173. Y.Bayat, M.M.Ahari-Mostafavi, N.Hasani. *Propell. Explos. Pyrotech.*, **39**, 649 (2014)
174. X.-F.Cao, B.-D.Li, M.Wang. *Chin. Chem. Lett.*, **25**, 423 (2014)
175. X.Liu, M.Lu. *J. Energ. Mater.*, **30**, 30 (2012)
176. A.B.Sheremetev, N.S.Alexandrova, K.Yu.Suponitsky, M.Yu.Antipin, V.A.Tartakovsky. *Mendeleev Commun.*, **20**, 249 (2010)
177. H.-P.Ren, Z.-W.Liu, J.Lu, Z.-T.Liu. *Ind. Eng. Chem. Res.*, **50**, 6615 (2011)
178. *Refrigerants — Environmental Properties. The Engineering Tool-Box* [Online]. https://www.engineeringtoolbox.com/Refrigerants-Environment-Properties-d_1220.html (accessed October 17, 2019)
179. R.E.Farncomb, G.W.Nauflett. *Waste Management*, **17**, 123 (1998)
180. I.V.Kuchurov, I.V.Fomenkov, S.G.Zlotin, V.A.Tartakovsky. *Mendeleev Commun.*, **22**, 67 (2012)
181. I.V. Kuchurov, S.S.Arabadzhi, M.N.Zharkov, L.L.Fershtat, S.G.Zlotin. *ACS Sustainable Chem. Eng.*, **6**, 2535 (2018)
182. Patent RU 2611009 (2017)
183. M.N.Zharkov, S.S.Arabadzhi, I.V.Kuchurov, S.G.Zlotin. *React. Chem. Eng.*, **4**, 1303 (2019)
184. Patent US 6177033 (2001)
185. Patent US 6527887 (2003)
186. Patent RU 2523472 (2014)
187. A.A.Guskov, I.V.Kuchurov, S.G.Zlotin. *Russ. J. Phys. Chem. B*, **9**, 1130 (2015)

188. Patent RU 2572419 (2016)
189. L.Kreplak, H.Wang, U.Aebi, X.-P.Kong. *J. Mol. Biol.*, **374**, 365 (2007)
190. N.Chanhan, M.E. Colclough, J.Hamid. In *Proceedings of the 6th Meeting on Supercritical Fluids*. (Nottingham, UK, 1999). P. 115
191. R.W.Millar, S.P.Philbin. *Tetrahedron*, **53**, 4371 (1997)
192. I.V.Kuchurov, I.V.Fomenkov, S.G.Zlotin. *Russ. Chem. Bull., Int. Ed.*, **59**, 2147 (2010)
193. B.P.Zhukov. *Energeticheskie Kondensirovannye Sistemy. Kratkiy Entsiklopedicheskiy Slovar* (Energetic Condensed Systems. Concise Encyclopedic Dictionary). (Ed. B.P.Zhukov). (Moscow: Yanus-K Publ., 2000)
194. Patent RU 2378251 (2010)
195. I.V.Kuchurov, I.V.Fomenkov, S.G.Zlotin. *Russ. Chem. Bull., Int. Ed.*, **58**, 2058 (2009)
196. M.N.Zharkov, I.V.Kuchurov, I.V.Fomenkov, S.G.Zlotin, V.A.Tartakovsky. *Mendeleev Commun.*, **25**, 15 (2015)
197. P.F.Pagoria, A.R.Mitchell, E.S. Jessop. *Propellants Explos. Pyrotech.*, **21**, 14 (1996)
198. I.V.Kuchurov, I.V.Fomenkov, S.G.Zlotin, V.A.Tartakovsky. *Mendeleev Commun.*, **23**, 81 (2013)
199. Patent US 4513148 (1985)
200. Patent US 4476322 (1983)
201. O.C.W.Allenby, G.F.Wright. *Can. J. Res.*, **25b**, 295 (1947)
202. S.C.Suri, R.D.Chapman. *Synthesis*, 743 (1988)
203. W.E.Bachmann, W.J.Horton, E.L.Jenner, N.W.MacNaughton, C.E.Maxwell. *J. Am. Chem. Soc.*, **72**, 3132 (1950)
204. Y.-H.Joo. J.M.Shreeve. *Chem. Commun.*, **46**, 142 (2010)
205. G.F.Wright, G.N.R.Smart. *Can. J. Res.*, **26**, 284 (1948)
206. L.J.Winters, D.B.Learn, S.C.Desai. *J. Org. Chem.*, **30**, 2471 (1965)
207. Patent RU 2610282 (2017)
208. M.N.Zharkov, I.V.Kuchurov, I.V.Fomenkov, V.A.Tartakovsky, I.V.Fedyanin, S.G.Zlotin. *Synthesis*, **49**, 1103 (2017)
209. S.G.Zlotin, A.M.Churakov, I.L.Dalinger, O.A.Luk'yanov, N.N.Makhova, A.Yu.Sukhorukov, V.A.Tartakovsky. *Mendeleev Commun.*, **27**, 535 (2017)
210. S.G.Zlotin, A.M.Churakov, O.A.Luk'yanov, N.N.Makhova, A.Yu.Sukhorukov, V.A.Tartakovsky. *Mendeleev Commun.*, **25**, 399 (2015)
211. N.Ono. *The Nitro Group in Organic Synthesis*. (New York: Wiley, 2002)
212. R.Ballini, M.Petrini. *ARKIVOC*, (ix), 195 (2009)
213. D.Seebach, E.W.Colvin, F.Lehr, T.Weller. *Chimia*, **33**, 1 (1979)
214. F.A.Luzzio. *Tetrahedron*, **57**, 915 (2001)
215. R.Ballini, G.Bosica, D.Fiorini, A.Palmieri, M.Petrini. *Chem. Rev.*, **105**, 933 (2005)
216. A.Noble, J.C.Anderson. *Chem. Rev.*, **113**, 2887 (2013)
217. E.Marqués-López, P.Merino, T.Tejero, R.P.Herrera. *Eur. J. Org. Chem.*, 2401 (2009)
218. S.L.Ioffe. In *Nitrile Oxides, Nitrones, and Nitronates in Organic Synthesis*. (Ed. H.Feuer). (Hoboken, Wiley, 2007). P. 435
219. A.A.Tabolin, A.Y.Sukhorukov, S.L.Ioffe, A.D.Dilman. *Synthesis*, **49**, 3255 (2017)
220. A.A.Tabolin, A.Y.Sukhorukov, S.L.Ioffe. *Chem. Rec.*, **18**, 1489 (2018)
221. L.Dong, C.Geng, P.Jiao. *J. Org. Chem.*, **80**, 10992 (2015)
222. X.Han, L.Dong, C.Geng, P.Jiao. *Org. Lett.*, **17**, 3194 (2015)
223. A.A.Tabolin, E.O.Gorbacheva, R.A.Novikov, Yu.A.Khoroshutina, Yu.V.Nelyubina, S.L.Ioffe. *Russ. Chem. Bull.*, **65**, 2243 (2016)
224. A.A.Mikhaylov, R.A.Novikov, Y.A.Khomutova, D.E.Arkhipov, A.A.Korlyukov, A.A.Tabolin, Y.V.Tomilov, S.L.Ioffe. *Synlett*, **25**, 2275 (2014)
225. A.S.Shved, A.A.Tabolin, R.A.Novikov, Y.V.Nelyubina, V.P.Timofeev, S.L.Ioffe. *Eur. J. Org. Chem.*, 5569 (2016)
226. A.V.Aksenov, N.A.Aksenov, O.N.Nadein, I.V. Aksenova. *Synlett*, 2628 (2010)
227. V.O.Smirnov, Y.A.Khomutova, V.A.Tartakovsky, S.L.Ioffe. *Eur. J. Org. Chem.*, 3377 (2012)
228. V.A.Tartakovsky. In *Lektsii Laureatov Demidovskoi Premii (1993 – 2004)* (Lectures of the Laureates of Demidov Prize). (Ekaterinburg: Izd. Ural Univ., 2006). P. 346
229. Y.A.Khomutova, V.O.Smirnov, H.Mayr, S.L.Ioffe. *J. Org. Chem.*, **72**, 9134 (2007)
230. V.O.Smirnov, S.L.Ioffe, A.A.Tishkov, Y.A.Khomutova, I.D.Nesterov, M.Yu.Antipin, W.A.Smit, V.A.Tartakovsky. *J. Org. Chem.*, **69**, 8485 (2004)
231. A.A.Mikhaylov, Y.A.Khomutova, D.E.Arkhipov, A.A.Korlyukov, S.L.Ioffe. *Mendeleev Commun.*, **24**, 374 (2014)
232. O.V.Fedorov, V.V.Levin, A.D.Volodin, M.I.Struchkova, A.A.Korlyukov, A.D.Dilman. *Tetrahedron Lett.*, **57**, 3639 (2016)
233. S.E.Denmark, A.Thorarensen. *Chem. Rev.*, **96**, 137 (1996)
234. P.Yu.Ushakov, A.A.Tabolin, S.L.Ioffe, A.Yu.Sukhorukov. *Eur. J. Org. Chem.*, 1888 (2019)
235. A.A.Tishkov, A.D.Dilman, V.I.Faustov, A.A.Birukov, K.S.Lysenko, P.A.Belyakov, S.L.Ioffe, Y.A.Strelenko, M.Yu.Antipin. *J. Am. Chem. Soc.*, **124**, 11358 (2002)
236. J.Y.Lee, Y.-T.Hong, S.Kim. *Angew. Chem., Int. Ed.*, **45**, 6182 (2006)
237. R.Henning, F.Lehr, D.Seebach. *Helv. Chim. Acta*, **59**, 2213 (1976)
238. D.Seebach, R.Henning, F.Lehr, J.Gonnermann. *Tetrahedron Lett.*, **18**, 1161 (1977)
239. D.Seebach, R.Henning, J.Gonnermann. *Chem. Ber.*, **112**, 234 (1979)
240. H.Feger, G.Simchen. *Liebigs Ann. Chem.*, **1986**, 1456 (1986)
241. A.D.Dilman, A.A.Tishkov, I.M.Lyapkalo, S.L.Ioffe, Yu.-A.Strelenko, V.A.Tartakovsky. *Synthesis*, 181 (1998)
242. A.D.Dilman, S.L.Ioffe, H.Mayr. *J. Org. Chem.*, **66**, 3196 (2001)
243. A.D.Dilman, I.M.Lyapkalo, S.L.Ioffe, Yu.A.Strelenko, V.A.Tartakovsky. *J. Org. Chem.*, **65**, 8826 (2000)
244. A.V.Ustinov, A.D.Dilman, S.L.Ioffe, Yu.A.Strelenko, W.A.Smit, V.A. Tartakovsky. *Mendeleev Commun.*, **13**, 74 (2003)
245. R.A.Kunetsky, A.D.Dilman, M.I.Struchkova, V.A.Tartakovsky, S.L.Ioffe. *Tetrahedron Lett.*, **46**, 5203 (2005)
246. Yu.A.Naumovich, I.S.Golovanov, A.Yu.Sukhorukov, S.L.Ioffe. *Eur. J. Org. Chem.*, 6209 (2017)
247. A.N.Semakin, A.Yu.Sukhorukov, A.V.Lesiv, Yu.A.Khomutova, S.L.Ioffe, K.A.Lyssenko. *Synthesis*, 2862 (2007)
248. Yu.A.Naumovich, A.O.Kokuev, A.Yu.Sukhorukov, S.L.Ioffe. *Synlett*, **29**, 1334 (2018)
249. A.V.Lesiv, S.L.Ioffe, Y.A.Strelenko, I.V.Bliznets, V.A.Tartakovsky. *Mendeleev Commun.*, **12**, 99 (2002)
250. P.A.Zhmurov, Yu.A.Khoroshutina, R.A.Novikov, I.S.Golovanov, A.Yu.Sukhorukov, S.L.Ioffe. *Chem. – Eur. J.*, **23**, 4570 (2017)
251. A.Yu.Sukhorukov, M.A.Kapatsyna, T.L.T. Yi, H.R. Park, Yu.A.Naumovich, P.A.Zhmurov, Y.A.Khomutova, S.L.Ioffe, V.A.Tartakovsky. *Eur. J. Org. Chem.*, 8148 (2014)
252. Yu.A.Naumovich, V.E.Buckland, D.A.Sen'ko, Yu.V.Nelyubina, Yu.A.Khoroshutina, A.Yu.Sukhorukov, S.L.Ioffe. *Org. Biomol. Chem.*, **14**, 3963 (2016)
253. V.S.Dorokhov, I.S.Golovanov, V.A.Tartakovsky, A.Yu.Sukhorukov, S.L.Ioffe. *Org. Biomol. Chem.*, **16**, 6900 (2018)
254. A.O.Kokuev, Yu.A.Antonova, V.S.Dorokhov, I.S.Golovanov, Yu.V.Nelyubina, A.A.Tabolin, A.Yu.Sukhorukov, S.L.Ioffe. *J. Org. Chem.*, **83**, 11057 (2018)

255. K.Tanda, A.Toyao, A.Watanabe, M.Sakamoto, T.Yamasaki. *Synlett*, **25**, 2953 (2014)
256. O.M.Berner, L.Tedeschi, D.Enders. *Eur. J. Org. Chem.*, 1877 (2002)
257. A.Z.Halimehjani, I.N.N.Namboothiri, S.E.Hooshmand. *RSC Adv.*, **4**, 31261 (2014)
258. A.Z.Halimehjani, I.N.N.Namboothiri, S.E.Hooshmand. *RSC Adv.*, **4**, 48022 (2014)
259. A.Z.Halimehjani, I.N.N.Namboothiri, S.E.Hooshmand. *RSC Adv.*, **4**, 51794 (2014)
260. B.-C.Hong, A.Raja, V.M.Sheth. *Synthesis*, **47**, 3257 (2015)
261. M.Ordóñez, C.Cativiela, I.Romero-Estudillo. *Tetrahedron: Asymmetry*, **27**, 999 (2016)
262. O.V.Maltsev, I.P.Beletskaya, S.G.Zlotin. *Russ. Chem. Rev.*, **80**, 1067 (2011)
263. S. Mukherjee, J. W. Yang, S. Hoffmann, B. List. *Chem. Rev.*, **107**, 5471 (2007)
264. O.Andrey, A.Vidonne, A.Alexakis. *Tetrahedron Lett.*, **44**, 7901 (2003)
265. O.Andrey, A.Alexakis, A.Tomassini, G.Bernardinelli. *Adv. Synth. Catal.*, **346**, 1147 (2004)
266. J.Fuska, B.Proksa, D.Uhrín. *Folia Microbiol.*, **33**, 238 (1988)
267. C.Douce, S.Moreau, F.Decloitre, F.Moulé. *Carcinogenesis*, **3**, 587 (1982)
268. W.T.Shier, H.K.Abbas, R.E.Baird, M.Ramezani, G.L.Sciumbato. *Toxin Rev.*, **26**, 343 (2007)
269. J.Wang, H.Li, B.Lou, L.Zu, H.Guo, W.Wang. *Chem. – Eur. J.*, **12**, 4321 (2006)
270. X.-Q.Chen, Y.-H.Chu. *Chin. Pharm. Bull.*, **14**, 243 (1998)
271. P.García-García, A.Ladépêche, R.Halder, B.List. *Angew. Chem., Int. Ed.*, **47**, 4719 (2008)
272. Y.Hayashi, T. Itoh, M. Ohkubo, H. Ishikawa. *Angew. Chem., Int. Ed.*, **47**, 4722 (2008)
273. K.S.Feu, A.F.de la Torre, S.Silva, M.A.F.de Moraes Junior, A.G.Corrêa, M.W.Paixão. *Green Chem.*, **16**, 3169 (2014)
274. H.Gotoh, H.Ishikawa, Y.Hayashi. *Org. Lett.*, **9**, 5307 (2007)
275. C.Palomo, A.Landa, A.Mielgo, M.Oiarbide, A.Puente, S.Vera. *Angew. Chem., Int. Ed.*, **46**, 8431 (2007)
276. P.Ramesh, D.Suman, K.S.N. Reddy. *Synthesis*, **50**, 211 (2018)
277. N.A.White, K.E.Ozboya, D.M.Flanigan, T.Rovis. *Asian J. Org. Chem.*, **3**, 442 (2014)
278. B.-C.Hong, R.Y.Nimje, M.-F.Wu, A.A.Sadani. *Eur. J. Org. Chem.*, 1449 (2008)
279. G.Holl, M.Straschill, T.Thomsen, J.P.Fischer, H.Kewitz. *Electroencephalogr. Clin. Neurophysiol.*, **82**, 445 (1992)
280. S.Yui, M.Mikami, M.Kitahara, M.Yamazaki. *Immunopharmacology*, **40**, 151 (1998)
281. N.K.Rana, H.Huang, J.C.-G.Zhao. *Angew. Chem., Int. Ed.*, **53**, 7619 (2014)
282. X.-L.Meng, T.Liu, Z.-W.Sun, J.-C.Wang, F.-Z.Peng, Z.-H.Shao. *Org. Lett.*, **16**, 3044 (2014)
283. Z.Sun, M.Zhou, X.Li, X.Meng, F.Peng, H.Zhang, Z.Shao. *Chem. – Eur. J.*, **20**, 6112 (2014)
284. H.Ishikawa, T.Suzuki, Y.Hayashi. *Angew. Chem., Int. Ed.*, **48**, 1304 (2009)
285. T.Mukaiyama, H.Ishikawa, H.Koshino, Y.Hayashi. *Chem. – Eur. J.*, **19**, 17789 (2013)
286. C.U.Kim, W.Lew, M.A.Williams, H.Liu, L.Zhang, S.Swaminathan, N.Bischofberger, M.S.Chen, D.B.Mendel, C.Y.Tai, W.G.Laver, R.C.Stevens. *J. Am. Chem. Soc.*, **119**, 681 (1997)
287. S.Zhu, S.Yu, Y.Wang, D.Ma. *Angew. Chem., Int. Ed.*, **49**, 4656 (2010)
288. J.Weng, Y.-B.Li, R.-B.Wang, G.Lu. *ChemCatChem*, **4**, 1007 (2012)
289. V.Hajzer, A.Latika, J.Durmis, R.Šebesta. *Helv. Chim. Acta*, **95**, 2421 (2012)
290. P.Tisovský, T.Peňaška, M.Mečiarová, R.Šebesta. *ACS Sustainable Chem. Eng.*, **3**, 3429 (2015)
291. Y.Hayashi. *Chem. Sci.*, **7**, 866 (2016)
292. Y.Hayashi, S.Umemiya. *Angew. Chem., Int. Ed.*, **52**, 3450 (2013)
293. C.D.Funk. *Science*, **294**, 1871 (2001)
294. S.V.Pansare, R.Lingampally, R.L.Kirby. *Org. Lett.*, **12**, 556 (2010)
295. L.E.Overman, J.Shim. *J. Org. Chem.*, **58**, 4662 (1993)
296. M.deGracia Retamosa, A.Ruiz-Olalla, T.Bello, A.deCózar, F.P.Cossío. *Angew Chem., Int. Ed.*, **57**, 668 (2018)
297. S.V.Pansare, R.Lingampally, R.Dyapa. *Eur. J. Org. Chem.*, 2235 (2011)
298. J.Zhou, G.Zhao, W.Jin, W.Zheng, Z.Chi. *Chin. Acad. Sci., Shanghai*, **9**, 107 (1988)
299. H.-Y.Min, H.-J.Chung, E.-H.Kim, S.Kim, E.-J.Park, S.K.Lee. *Biochem. Pharmacol.*, **80**, 1356 (2010)
300. W.Gao, A.P.-C.Chen, C.-H.Leung, E.A.Gullen, A.Fürstner, Q.Shi, L.Wei, K.-H.Lee, Y.-C.Cheng. *Bioorg. Med. Chem. Lett.*, **18**, 704 (2008)
301. S.V.Pansare, R.Dyapa. *Org. Biomol. Chem.*, **10**, 6776 (2012)
302. A.Al-Shamma, S.D.Drake, L.E.Guagliardi, L.A.Mitscher, J.K.Swayze. *Phytochemistry*, **21**, 485 (1982)
303. E.Krmpotic, N.R.Farnsworth, W.M.Messmer. *J. Pharm. Sci.*, **61**, 1508 (1972)
304. G.R.Dchaldson, M.R.Atkinson, A.W.Murray. *Biochem. Biophys. Res. Commun.*, **31**, 104 (1968)
305. A.S.Kucherenko, V.G.Lisnyak, A.A.Kostenko, S.V.Kochetkov, S.G.Zlotin. *Org. Biomol. Chem.*, **14**, 9751 (2016)
306. S.P.Chavan, S.Garai, K.P.Pawar. *Tetrahedron Lett.*, **54**, 2137 (2013)
307. M.Tsakos, C.G.Kokotos, G.Kokotos. *Adv. Synth. Catal.*, **354**, 740 (2012)
308. F.Felluga, V.Gombac, G.Pitacco, E.Valentin. *Tetrahedron: Asymmetry*, **16**, 1341 (2005)
309. E.J.Corey, F.-Y.Zhang. *Org. Lett.*, **2**, 4257 (2000)
310. J.Tian, J.Zhong, Y.Li, D.Ma. *Angew. Chem., Int. Ed.*, **53**, 13885 (2014)
311. M.von Itzstein, W.-Y.Wu, G.B.Kok, M.S.Pegg, J.C.Dyason, B.Jin, T.V.Phan, M.L.Smythe, H.F.White, S.W.Oliver, P.M.Colman, J.N.Varghese, D.M.Ryan, J.M.Woods, R.C.Bethell, V.J.Hotham, J.M.Cameron, C.R.Penn. *Nature (London)*, **363**, 418 (1993)
312. T.Honda, T.Masuda, S.Yoshida, M.Arai, S.Kaneko, M.Yamashita. *Bioorg. Med. Chem. Lett.*, **12**, 1925 (2002)
313. H.Ouchi, A.Asahina, T.Asakawa, M.Inai, Y.Hamashima, T.Kan. *Org. Lett.*, **16**, 1980 (2014)
314. K.Konno, H.Shirahama, T.Matsumoto. *Tetrahedron Lett.*, **24**, 939 (1983)
315. H.Shinozaki, M.Ishida, T.Okamoto. *Brain Res.*, **399**, 395 (1986)
316. M.Maruyama, K.Takeda. *Brain Res.*, **504**, 328 (1989)
317. D.M.Barnes, J.Ji, M.G.Fickes, M.A.Fitzgerald, S.A.King, H.E.Morton, F.A.Plagge, M.Preskill, S.H.Wagaw, S.J.Wittenberger, J.Zhang. *J. Am. Chem. Soc.*, **124**, 13097 (2002)
318. Z.Pei, X.Li, T.W. von Geldern, K.Longenecker, D.Pireh, K.D.Stewart, B.J.Backes, C.Lai, T.H.Lubben, S.J.Ballaron, D.W.A.Beno, A.J.Kempf-Grote, H.L.Sham, J.M.Trevillyan. *J. Med. Chem.*, **50**, 1983 (2007)
319. J.R.Wu-Wong, D.B.Dixon, W.J.Chiou, B.D.Dayton, E.I.Novosad, A.L.Adler, J.L.Wessale, S.V.Calzadilla, L.Hernandez, K.C.Marsh, G.Liu, B.Szczepankiewicz, T.W.von Geldern, T.J.Opgenorth. *Eur. J. Pharmacol.*, **366**, 189 (1999)
320. L.Wen, F.Tang, C.Ge, X.Wang, Z.Han, J.Wu. *Synth. Commun.*, **42**, 3288 (2012)
321. J.Chen, J.Chen, Y.Xie, H.Zhang. *Angew. Chem., Int. Ed.*, **51**, 1024 (2012)
322. R.A.Pilli, M.C.Ferreira de Oliveira. *Nat. Prod. Rep.*, **17**, 117 (2000)
323. X.Yu, W.Wang. *Chem. – Asian J.*, **3**, 516 (2008)

324. C.Nájera, M.Yus. *Tetrahedron Lett.*, **56**, 2623 (2015)
325. J.Alemán, A.Parra, H.Jiang, K.A.Jørgensen. *Chem. – Eur. J.*, **17**, 6890 (2011)
326. T.Okino, Y.Hoashi, T.Furukawa, X.Xu, Y.Takemoto. *J. Am. Chem. Soc.*, **127**, 119 (2005)
327. Y.Takemoto. *Chem. Pharm. Bull.*, **58**, 593 (2010)
328. F.Li, Y.-Z.Li, Z.-S.Jia, M.-H.Xu, P.Tian, G.-Q.Lin. *Tetrahedron*, **67**, 10186 (2011)
329. J.-m.Liu, X.Wang, Z.-m.Ge, Q.Sun, T.-m.Cheng, R.-t.Li. *Tetrahedron*, **67**, 636 (2011)
330. C.P.Taylor, M.G.Vartanian, Y.Po-Wai, C.Bigge, N.Suman-Chauhan, D. R.Hill. *Epilepsy Res.*, **14**, 11 (1993)
331. A.G.Nigmatov, I.V.Kuchurov, D.E.Siyutkin, S.G.Zlotin. *Tetrahedron Lett.*, **53**, 3502 (2012)
332. H.Y.Bae, C.E. Song. *ACS Catal.*, **5**, 3613 (2015)
333. S.Narayan, J.Muldoon, M.G.Finn, V.V.Fokin, H.C.Kolb, K.B.Sharpless. *Angew. Chem., Int. Ed.*, **44**, 3275 (2005)
334. R.S.Tukhvatshin, A.S.Kucherenko, Yu.V.Nelyubina, S.G.Zlotin. *ACS Catal.*, **7**, 2981 (2017)
335. K.L.Kimmel, J.D.Weaver, J.A.Ellman. *Chem. Sci.*, **3**, 121 (2012)
336. O.Bassas, J.Huuskonen, K.Rissanen, A.M.P.Koskinen. *Eur. J. Org. Chem.*, 1340 (2009)
337. R.Baran, E.Veverková, A.Škvorcová, R.Šebesta. *Org. Biomol. Chem.*, **11**, 7705 (2013)
338. J.P.Malerich, K.Hagihara, V.H.Rawal. *J. Am. Chem. Soc.*, **130**, 14416 (2008)
339. P.S.Hynes, P.A.Stupple, D.J.Dixon. *Org. Lett.*, **10**, 1389 (2008)
340. Patent US 4012495A (1975)
341. Patent US 24721723 (1986)
342. M.S.Yu, I.Lantos, Z.-Q.Peng, J.Yu, T.Cacchio. *Tetrahedron Lett.*, **41**, 5647 (2000)
343. H.Jin, S.T.Kim, G.-S.Hwang, D.H.Ryu. *J. Org. Chem.*, **81**, 3263 (2016)
344. J.H.Sim, C.E.Song. *Angew. Chem., Int. Ed.*, **56**, 1835 (2017)
345. Y.Hoashi, T.Yabuta, P.Yuan, H.Miyabe, Y.Takemoto. *Tetrahedron*, **62**, 365 (2006)
346. J.Tsuji, I.Minami. *Acc. Chem. Res.*, **20**, 140 (1987)
347. P.Elsner, H.Jiang, J.B.Nielsen, F.Pasi, K.A.Jørgensen. *Chem. Commun.*, 5827 (2008)
348. T.Weber, K.Welzel, S.Pelzer, A.Vente, W.Wohlleben. *J. Biotechnol.*, **106**, 221 (2003)
349. P.Jakubec, D.M.Cockfield, D.J.Dixon. *J. Am. Chem. Soc.*, **131**, 16632 (2009)
350. J.J.Kobayashi, D.Watanabe, N.Kawasaki, M.Tsuda. *J. Org. Chem.*, **62**, 9236 (1997)
351. A.F.Kyle, P.Jakubec, D.M.Cockfield, E.Cleator, J.Skidmore, D.J.Dixon. *Chem. Commun.*, **47**, 10037 (2011)
352. T.A.Johnson, M.D.Curtis, P.Beak. *J. Am. Chem. Soc.*, **123**, 1004 (2001)
353. T.A.Johnson, D.O.Jang, B.W.Slafer, M.D.Curtis, P.Beak. *J. Am. Chem. Soc.*, **124**, 11689 (2002)
354. D.Polet, A.Alexakis. *Tetrahedron Lett.*, **46**, 1529 (2005)
355. J.-P.Rieu, A.Boucherle, H.Cousse, G.Mouzin. *Tetrahedron*, **42**, 4095 (1986)
356. T.Bui, S.Syed, C.F.Barbas III. *J. Am. Chem. Soc.*, **131**, 8758 (2009)
357. T.Matsuura, L.E.Overman, D.J.Poon. *J. Am. Chem. Soc.*, **120**, 6500 (1998)
358. K.Asakawa, N.Noguchi, S.Takashima, M.Nakada. *Tetrahedron: Asymmetry*, **19**, 2304 (2008)
359. D.J.Triggle, J.M.Mitchell, R.Filler. *CNS Drug Rev.*, **4**, 87 (1998)
360. A.G.M.Barrett. *Chem. Soc. Rev.*, **20**, 95 (1991)
361. D.J.Buchanan, D.J.Dixon, B.E.Looker. *Synlett*, 1948 (2005)
362. N.J.Adderley, D.J.Buchanan, D.J.Dixon, D.I.Laine. *Angew. Chem., Int. Ed.*, **42**, 4241 (2003)
363. P.Dinér, M.Nielsen, S.Bertelsen, B.Niess, K.A.Jørgensen. *Chem. Commun.*, 3646 (2007)
364. M.F.Rafferty, D.S.Wilson, J.A.Monn, P.Krass, R.T.Borchardt, G.L.Grunewald. *J. Med. Chem.*, **25**, 1198 (1982)
365. A.Kamimura, Y.Nagata, A.Kadowaki, K.Uchida, H.Uno. *Tetrahedron*, **63**, 11856 (2007)
366. J.P.Michael. *The Alkaloids*. Vol. 75. (Ed. H.-J.Knölker). (Oxford: Academic Press, 2016)
367. M.G.Vinogradov, O.V.Turova, S.G.Zlotin. *Org. Biomol. Chem.*, **17**, 3670 (2019)
368. R.A.Fromtling. *Clin. Microbiol. Rev.*, **1**, 187 (1988)
369. P.Benfield, P.Stephen. *Drugs*, **35**, 143 (1988)
370. K.L.Kimmel, M.T.Robak, J.A.Ellman. *J. Am. Chem. Soc.*, **131**, 8754 (2009)
371. K.L.Kimmel, M.T.Robak, S.Thomas, M.Lee, J.A.Ellman. *Tetrahedron*, **68**, 2704 (2012)
372. M.T.Robak, M.Trincado, J.A.Ellman. *J. Am. Chem. Soc.*, **129**, 15110 (2007)
373. R.Kowalczyk, A.E.Nowak, J.Skarżewski. *Tetrahedron: Asymmetry*, **24**, 505 (2013)
374. W.Yang, D.-M.Du. *Org. Biomol. Chem.*, **10**, 6876 (2012)
375. T.C.Birdsall. *Alt. Med. Rev.*, **3**, 128 (1998)
376. Patent RU 2233267 (2004)
377. Patent RU 2292329 (2007)
378. Patent RU 2273652 (2006)
379. Patent RU 2415892 (2011)
380. A.L.Rusanov, L.G.Komarova, M.P.Prigozhina, A.A.Askadskii, S.A.Shevelev, M.D.Dutov, O.V.Serushkina, V.Yu.Vogtekunas, M.J.M.Abadie. *Polymer Science, Ser. B*, **50**, 70 (2008)
381. A.L.Rusanov, *E.G.*Bulycheva, M.G.Bugaenko, A.Yu.Leikin, S.A.Shevelev, M.D.Dutov, O.V.Serushkina, V.Yu.Voitekunas, M.Abadi. *Polymer Science, Ser. C*, **51**, 3 (2009)
382. A.L.Rusanov, *E.G.*Bulycheva, M.G.Bugaenko, S.A.Shevelev, M.D.Dutov, O.V.Serushkina. *Polymer Science, Ser. B*, **52**, 292 (2010)
383. S.Shevelev, A.Starosotnikov. In *Metal Free C – H Functionalization of Aromatics*. (Eds V.Charushin, O.Chupakhin). (Cham: Springer) *Top. Heterocycl. Chem.*, **37**, 107 (2014)
384. S.A.Shevelev, A.M.Starosotnikov. *Chem. Heterocycl. Compd.*, **49**, 92 (2013)
385. S.A.Shevelev, M.D.Dutov, O.V.Serushkina. *Russ. Chem. Bull.*, **44**, 2424 (1995)
386. V.V.Rozhkov. *Tetrahedron*, **70**, 3595 (2014)
387. S.G.Zlotin, P.G.Kislitsin, A.V.Samet, E.A.Serebryakov, L.D.Konyushkin, V.V.Semenov, A.C.Buchanan III, A.A.Gakh. *J. Org. Chem.*, **65**, 8430 (2000)
388. O.Yu.Sapozhnikov, V.V.Mezhnev, M.D.Dutov, V.V.Kachala, N.A.Popov, S.A. Shevelev. *Russ. Chem. Bull.*, **54**, 711 (2005)
389. O.Yu.Sapozhnikov, M.D.Dutov, M.A.Korolev, V.V.Kachala, V.I.Kadentsev, S.A.Shevelev. *Russ. Chem. Bull.*, **53**, 588 (2004)
390. A.Nour, T.Hayashi, M.Chan, S.Yao, R.I.Tawatao, B.Crain, I.F.Tsigelny, V.L.Kouznetsova, A.Ahmadiiveli, K.Messer, M.Pu, M.Corr, D.A.Carson, H.B.Cottam. *Bioorg. Med. Chem. Lett.*, **24**, 4931 (2014)
391. S.S.Vorob'ev, M.D.Dutov, I.A.Vatsadze, E.P.Petrosyan, V.V.Kachala, Yu.A.Strelenko, S.A.Shevelev. *Russ. Chem. Bull.*, **56**, 1020 (2007)
392. G.V.Kokurkina, M.D.Dutov, S.A.Shevelev, S.V.Popkov, A.V.Zakharov, V.V.Poroikov. *Eur. J. Med. Chem.*, **46**, 4374 (2011)
393. S.G.Zlotin, P.G.Kislitsin, F.A.Kucherov, A.A.Gakh. *Heterocycles*, **68**, 1109 (2006)
394. S.G.Zlotin, P.G.Kislitsyn, A.I.Podgursky, A.V.Samet, V.V.Semenov, A.C.Buchanan III, A.A.Gakh. *J. Org. Chem.*, **65**, 8439 (2000)

395. E.A.Serebryakov, P.G.Kislitsin, V.V.Semenov, S.G.Zlotin. *Synthesis*, 1659 (2001)
396. A.I.Gerasyuto, S.G.Zlotin, V.V.Semenov. *Synthesis*, 300 (2001)
397. M.A.Bastrakov, A.M.Starosotnikov, S.A.Shevelev. *ARKIVOC*, (iv), 88 (2009)
398. V.M.Vinogradov, I.L.Dalinger, A.M.Starosotnikov, S.A.Shevelev. *Russ. Chem. Bull.*, **50**, 464 (2001)
399. A.M.Starosotnikov, V.V.Kachala, A.V.Lobach, V.M.Vinogradov, S.A.Shevelev. *Russ. Chem. Bull.*, **52**, 1782 (2003)
400. M.A.Bastrakov, A.M.Starosotnikov, V.V.Kachala, E.N.Nesterova, S.A.Shevelev. *Russ. Chem. Bull.*, **56**, 1603 (2007)
401. O.Yu.Sapozhnikov, E.V.Smirnova, M.D.Dutov, V.V.Kachala, S.A.Shevelev. *Mendeleev Commun.*, **15**, 200 (2005)
402. S.A.Shevelev, I.L.Dalinger, T.I.Cherkasova. *Tetrahedron Lett.*, **42**, 8539 (2001)
403. A.M.Starosotnikov, A.V.Lobach, Yu.A.Khomutova, S.A.Shevelev. *Russ. Chem. Bull.*, **55**, 543 (2006)
404. A.M.Starosotnikov, V.V.Nikol'skiy, A.N. Borodulya, V.V.Kachala, M.A.Bastrakov, V.N.Solkan, S.A.Shevelev. *Asian J. Org. Chem.*, **5**, 685 (2016)
405. M.A.Bastrakov, A.I.Leonov, A.M.Starosotnikov, I.V.Fedyanin, S.A.Shevelev. *Russ. Chem. Bull.*, **62**, 1052 (2013)
406. A.M.Starosotnikov, V.V.Nikol'skiy, M.A.Bastrakov, V.V.Kachala, A.A.Pavlov, B.I.Ugrak, S.A.Shevelev. *ChemistrySelect*, **3**, 1230 (2018)
407. P.Devi, J.S.Sandhu. *J. Chem. Soc. Chem. Commun.*, 990 (1983)
408. M.A.Bastrakov, A.M.Starosotnikov, S.Yu.Pechenkin, V.V.Kachala, I.V.Glukhov, S.A.Shevelev. *J. Heterocycl. Chem.*, **47**, 893 (2010)
409. L.S.Konstantinova, M.A.Bastrakov, A.M.Starosotnikov, I.V.Glukhov, K.A.Lysov, O.A.Rakitin, S.A.Shevelev. *Mendeleev Commun.*, **20**, 353 (2010)
410. M.A.Bastrakov, A.M.Starosotnikov, A.A.Pavlov, I.L.Dalinger, S.A.Shevelev. *Chem. Heterocycl. Compd.*, **52**, 690 (2016)
411. S.Lee, I.Chataigner, S.R.Piettre. *Angew. Chem., Int. Ed.*, **50**, 472 (2011)
412. S.Lee, S.Diab, P.Queval, M.Sebban, I.Chataigner, S.R.Piettre. *Chem.–Eur. J.*, **19**, 7181 (2013)
413. A.M.Starosotnikov, M.A.Bastrakov, S.Yu.Pechenkin, M.A.Leontieva, V.V.Kachala, S.A.Shevelev. *J. Heterocycl. Chem.*, **48**, 824 (2011)
414. S.Yu.Pechenkin, A.M.Starosotnikov, M.A.Bastrakov, I.V.Glukhov, S.A.Shevelev. *Russ. Chem. Bull.*, **61**, 74 (2012)
415. A.M.Starosotnikov, M.A.Bastrakov, V.V.Kachala, I.V.Fedyanin, S.A.Shevelev, I.L.Dalinger. *Chem. Select*, **3**, 9773 (2018)
416. M.A.Bastrakov, A.M.Starosotnikov, V.V.Kachala, I.V.Fedyanin, S.A.Shevelev. *Asian J. Org. Chem.*, **4**, 146 (2015)
417. A.M.Starosotnikov, M.A.Bastrakov, V.V.Kachala, P.A.Belyakov, I.V.Fedyanin, S.A.Shevelev. *Synlett*, **23**, 2400 (2012)
418. Yu.P.Semenyuk, A.S.Kochubei, P.G.Morozov, O.N.Burov, M.E.Kletskii, S.V.Kurbatov. *Chem. Heterocycl. Compd.*, **50**, 1731 (2014)
419. Yu.P.Semenyuk, P.G.Morozov, M.E.Kletskii, O.N.Burov, A.S.Cheprasov, S.V.Kurbatov. *Russ. J. Org. Chem.*, **51**, 449 (2015)
420. B.M.Trost, V.Ehmke, B.M.O'Keefe, D.A. Bringley. *J. Am. Chem. Soc.*, **136**, 8213 (2014)
421. P.MacCormack, J.C.Halle, M.J.Pouet, F.Terrier. *J. Org. Chem.*, **53**, 4407 (1988)
422. J.-C.Halle, D.Vichard, M.-J.Pouet, F.Terrier. *J. Org. Chem.*, **62**, 7178 (1997)
423. P.Sepulcri, J.C.Halle, R.Goumont, D.Riou, F.Terrier. *J. Org. Chem.*, **64**, 9254 (1999)
424. D.Vichard, T.Boubaker, F.Terrier, M.-J.Pouet, J.M.Dust, E.Buncel. *Can. J. Chem.*, **79**, 1617 (2001)
425. S.Lakhdar, R.Goumont, T.Boubaker, M.Mokhtari, F.Terrier. *Org. Biomol. Chem.*, **4**, 1910 (2006)
426. V.V.Mezhnev, M.D.Dutov, S.A.Shevelev. *Russ. Chem. Bull.*, **58**, 476 (2009)
427. A.M.Starosotnikov, M.A.Leontieva, M.A.Bastrakov, A.V.Puchnin, V.V.Kachala, S.A.Shevelev *Mendeleev Commun.*, **20**, 165 (2010)
428. S.Kurbatov, R.Goumont, J.Marrot, F.Terrier. *Tetrahedron Lett.*, **45**, 1037 (2004)
429. D.V.Steglenko, M.E.Kletsky, S.V.Kurbatov, A.V.Tatarov, V.I.Minkin, R.Goumont, F.Terrier. *J. Phys. Org. Chem.*, **22**, 298 (2009)
430. M.A.Bastrakov, A.M.Starosotnikov, V.V.Kachala, I.L.Dalinger, S.A.Shevelev. *Chem. Heterocycl. Compd.*, **51**, 496 (2015)
431. A.M.Starosotnikov, M.A.Bastrakov, A.A.Pavlov, I.V.Fedyanin, I.L.Dalinger, S.A.Shevelev. *Mendeleev Commun.*, **26**, 217 (2016)
432. M.A.Bastrakov, A.M.Starosotnikov, I.V.Fedyanin, V.V.Kachala, S.A.Shevelev. *Mendeleev Commun.*, **24**, 203 (2014)
433. M.S.Klenov, A.A.Guskov, O.V.Anikin, A.M.Churakov, Yu.A.Strelenko, I.V.Fedyanin, K.A.Lyssenko, V.A.Tartakovsky. *Angew. Chem., Int. Ed.*, **55**, 11472 (2016)
434. A.A.Guskov, M.S.Klenov, A.M.Churakov, V.A.Tartakovsky. *Russ. Chem. Bull.*, **65**, 2763 (2016)
435. O.A.Luk'yanov, N.I.Shlykova, G.V.Pokhvisneva, T.V.Ternikova, S.V.Nikitin, G.A.Smirnov, Yu.V.Nelubina, P.V.Dorovatovskii, T.S.Kon'kova, N.V.Murav'yov, A.N.Pivkina. *Russ. Chem. Bull.*, **66**, 1066 (2017)
436. O.A.Luk'yanov, N.I.Shlykova, G.V.Pokhvisneva, T.V.Ternikova, K.A.Monogarov, D.B.Meerov, Yu.V.Nelyubina, P.V.Dorovatovskii, T.S.Kon'kova. *Russ. Chem. Bull.*, **68**, 110 (2019)
437. D.Kumar, G.H.Imler, D.A.Parrish, J.M.Shreeve. *J. Mater. Chem. A*, **5**, 10437 (2017)
438. D.Fischer, J.L.Gottfried, T.M.Klapötke, K.Karaghiosoff, J.Stierstorfer, T.G.Witkowski. *Angew Chem., Int. Ed.*, **55**, 16132 (2016)
439. P.Yin, J.Zhang, G.H.Imler, D.A.Parrish, J.M.Shreeve. *Angew Chem., Int. Ed.*, **56**, 8834 (2017)
440. P.Yin, C.He, J.M.Shreeve. *J. Mater. Chem. A*, **4**, 1514 (2016)
441. Patent RU 2689406 (2019)
442. A.V.Aksenov, A.N.Smirnov, N.A.Aksenov, A.S.Bijieva, I.V.Aksenova, M.Rubin. *Org. Biomol. Chem.*, **13**, 4289 (2015)
443. M.Zhang, J.Zhou, J.Kan, M.Wang, W.Su, M.Hong. *Chem. Commun.*, **46**, 5455 (2010)
444. Y.A.Volkova, E.B.Averina, D.A.Vasilenko, K.N.Sedenkova, Y.K.Grishin, P.Bruheim, T.S.Kuznetsova, N.S.Zefirov. *J. Org. Chem.*, **84**, 3192 (2019)
445. E.B.Averina, T.S.Kuznetsova, N.S.Zefirov. *Synlett*, 1543 (2009)
446. L.M.Barton, F.T.Edwards, E.C.Johnson, E.J.Bukowski, R.C.Sausa, E.F.C.Byrd, J.A.Orlicki, J.J.Sabatini, R.S.Baran. *J. Am. Chem. Soc.,* **141**, 12531 (2019)