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Methods of synthesis and properties of hexanitrohexaazaisowurtzitane

S V Sysolyatin, A A Lobanova, Yu T Chernikova, G V Sakovich

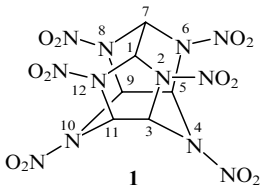
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Abstract. Methods of synthesis and properties of 2,4,6,8,10,12-hexanitro-2,4,6,8,10,12-hexaazatetracyclo[5.5.0.0^{3,11}.0^{5,9}]dodecane (also referred to as CL-20 or HNIW), a highly energetic polycyclic nitramine, are surveyed. The bibliography includes 49 references.

I. Introduction

The progress in the defence technologies is naturally related to the development of novel more efficient components of mixed solid propellants, explosive compositions and gunpowders. A possible route to accomplish this task consists of the preparation of highly energetic compounds that provide the explosion power superior to any existing substance. According to the theoretical predictions on the physicochemical and explosion characteristics, polycyclic nitramines, in particular, hexanitrohexaazaisowurtzitane, 2,4,6,8,10,12-hexanitro-2,4,6,8,10,12-hexaazatetracyclo[5.5.0.0^{3,11}.0^{5,9}]dodecane (**1**), HNIW, CL-20, a unique representative of this class of compounds, hold much promise in this respect.



1

An HNIW molecule possesses a compact structure, so that both the density † and energetic characteristics of **1** are exceptionally high (Table 1).[1–3]

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Table 1. Physicochemical and energetic characteristics of hexanitrowurtzitane.

Parameter	Value	Ref.
Molecular formula	$C_6H_6N_{12}O_{12}$	
Molecular mass	438.186	
Decomposition temperature /°C	250 – 260	1, 2
Density (ρ) /g cm^{-3}	2.044	2
Enthalpy of formation (ΔH_f°) /kJ mol^{-1}	377.411	3
Oxygen balance (CO_2 and H_2O) (%)	20	
Calculated detonation rate /km s^{-1}	9.38	1

Hexanitrohexaazaisowurtzitane was synthesised for the first time in 1987 at the Naval Air Warfare Center (USA).[4] Since then, intense investigations into optimisation of the methods for its synthesis as well as technologies of its production and preparation of explosives and propellants for diverse applications based on it are being conducted.

A pilot plant for the production of HNIW with a performance of 200 kg of the target product per load was designed in 1990 by the Thiokol corporation (USA).[4]

In the present review, the published data on the methods for the synthesis of polycyclic nitramine **1** and studies of its physicochemical properties are considered systematically. In all the documented methods for the synthesis of compound **1**, the overall process can be divided into two steps: first, construction of the hexanitrohexaazaisowurtzitane cage and, second, substitution of the nitro groups for functional groups at the nitrogen atoms.

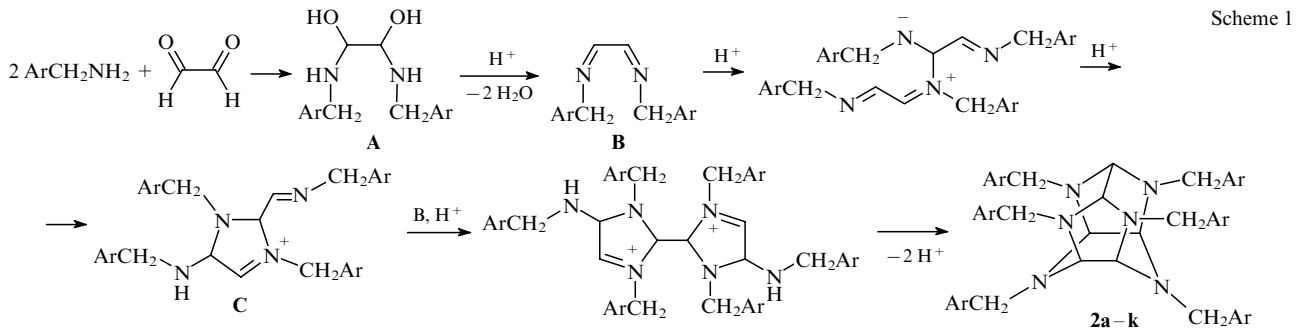
II. Construction of the hexanitrohexaazaisowurtzitane cage

The only available method for the construction of the hexanitrohexaazaisowurtzitane cage is based on the condensation of glyoxal ‡ with benzylamine or its derivatives.[5,6] A mechanism suggested for this reaction is shown in Scheme 1.

Two intermediates, *viz*., diol **A** and diimine **B**, have been isolated and identified.[5] The reaction was carried out in aqueous

† The detonation pressure of an energetic compound is proportional to its density.
‡ 2,3-Dihydroxy-1,4-dioxane can be used instead of glyoxal.

Scheme 1



Ar = Ph (**a**), C_6H_4Me-*p* (**b**), C_6H_4Me-*o* (**c**), C_6H_4OMe-*p* (**d**), C_6H_4OMe-*o* (**e**), $C_6H_3(OMe)_2$-3,4 (**f**), $C_6H_4Pr^i$-*p* (**g**), C_6H_4Cl-*p* (**h**), C_6H_4Cl-*o* (**i**), C_6H_4F-*o* (**j**), C_6H_4Br-*o* (**k**).

acetonitrile,[5] methanol,[6,7] ethanol [7,8] or isopropyl alcohol [7] in the presence of an acidic catalyst at 0–25 °C. Various organic and inorganic acids, such as formic,[7] acetic,[2] salicylic, *p*-toluenesulfonic,[9] nitric [1] and perchloric acids, were used as catalysts.[10] Table 2 summarises the yields and properties of the products obtained.

Table 2. Yields and properties of the condensation products of glyoxal with benzylamine derivatives.

Compound	Ar	Molecular formula	Melting point /°C	Yield (%)	Ref.
2a	Ph	$C_{48}H_{48}N_6$	153–157	80	5
			153	67	6
2b	C_6H_4Me-*p*	$C_{54}H_{60}N_6$	172–174	68	5
			174	66	6
2c	C_6H_4Me-*o*	$C_{54}H_{60}N_6$	203	45	6
2d	C_6H_4OMe-*p*	$C_{54}H_{60}N_6O_6$	148–150	60	5
2e	C_6H_4OMe-*o*	$C_{54}H_{60}N_6O_6$	148–150	60	5
			136	28	6
2f	$C_6H_3(OMe)_2$-3,4	$C_{60}H_{72}N_6O_{12}$	160–161	50	5
2g	$C_6H_3Pr^i$-*p*	$C_{66}H_{84}N_6$	144–145	24	5
2h	C_6H_4Cl-*p*	$C_{48}H_{42}Cl_6N_6$	212–214	46	5
			191	20	6
2i	C_6H_4Cl-*o*	$C_{48}H_{42}Cl_6N_6$	208–211	68	5
			182	15	6
2j	C_6H_4F-*o*	$C_{48}H_{42}F_6N_6$	126	33	6
2k	C_6H_4Br–*o*	$C_{48}H_{42}Br_6N_6$	210	22	6

As can be judged from Table 2, the highest yield was obtained in the case of the condensation of glyoxal and unsubstituted benzylamine. The reaction product, 2,4,6,8,10,12-hexabenzyl-2,4,6,8,10,12-hexaazatetracyclo[5.5.0.0^{3,11}.0^{5,9}]dodecane (**2a**), represents a white non-hygroscopic crystalline substance, which decomposes in acetic acid.[5–7] UV spectroscopic studies have shown that the decomposition of the hexabenzyl derivative **2a** in aqueous acetonitrile is catalysed by acids and probably involves protonation followed by decomposition of the isowurtzitane cage.[6]

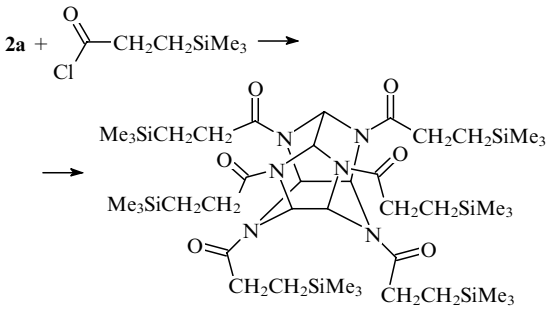
The molecular structures of the condensation products **2b** (see Ref. 6), **2d** (see Ref. 5) and **2h** (see Ref. 7) have been confirmed by the data from IR and NMR spectroscopy and X-ray crystallography.

No compounds with the isowurtzitane cage could be synthesised upon condensation of glyoxal with *o*-aminobenzylamine, acetamide and *p*-carboxybenzylamine.[7,11]

III. Preparation of hexaazaisowurtzitane derivatives to be used in the synthesis of hexanitrohexaazawurtzitane

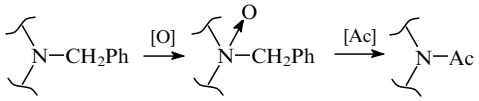
No hexanitrohexaazaisowurtzitane was formed upon direct nitrolysis of the hexabenzyl derivative **2a** due to both competitive nitration of the benzene rings and instability of the intermediates. Therefore, the benzyl groups at the nitrogen atoms in **2a** should be first replaced by groups that are susceptible to nitrolysis, *e.g.*, AlkC(O), CHO, NO, *etc*.

Preparation of acylated hexaazaisowurtzitane is an especially promising direction for the synthesis of HNIW, since typically the acyl groups at the nitrogen atoms can easily be replaced by nitro groups. Direct acidolysis of **2a** with trimethylsilylpropionyl chloride is documented.[12]

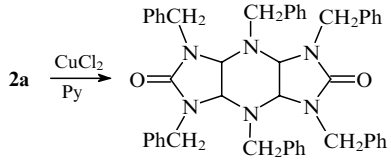


Treatment of the hexabenzyl derivative **2a** with such acylation agents as acetic, chloroacetic and trifluoroacetic anhydrides results only in its extensive decomposition and resinification.[11]

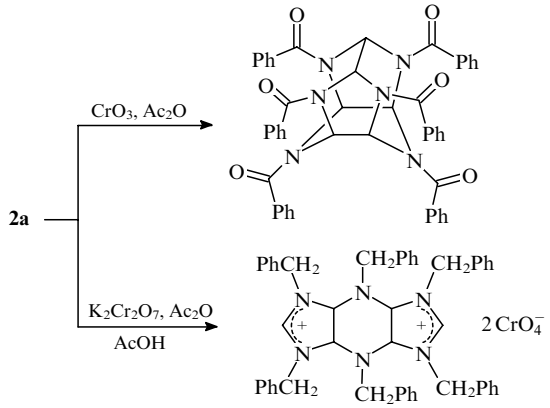
Another approach to the synthesis of the hexaazaisowurtzitane *N*-acetyl derivative consists of the oxidation of **2a** to the respective *N*-oxide followed by the Polonovsky rearrangement.



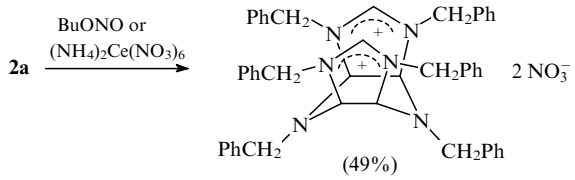
The selection of a proper oxidant is a non-trivial problem, since oxidation of the hexabenzyl derivative **2a** often results in the decomposition of the polycyclic cage. For instance, it has been established experimentally that the C(1)–C(7) bond is cleaved upon oxidation of **2a** with copper(II) chloride in the presence of pyridine to yield 1,3,4,5,7,8-hexabenzyl-2,6-dioxo-*cis*-*cisoid*-*cis*-hexahydro-1*H*,5*H*′-diimidazo[4,5-*b*:4′,5′-*e*]pyrazine.[13]



It is known that Cr(VI) species is the oxidant of choice for the benzylic C—H bonds. Therefore, Oiu *et al.*[14] tested various Cr(VI) compounds in the oxidation of the hexabenzyl derivative **2a**. In particular, the oxidation of **2a** with CrO_3 in acetone afforded the target product, *viz*., hexabenzoylhexaazaisowurtzitane,[14] whereas the oxidation with the system $K_2Cr_2O_7$ – Ac_2O – AcOH resulted in the cleavage of the C(1)—C(7) bond to yield diimidazolinopyrazinium chromate.

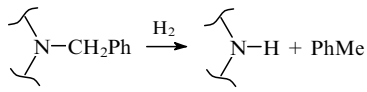


An analogous product was obtained in the oxidation of **2a** with butyl nitrite or ammonium cerium nitrate.[15]



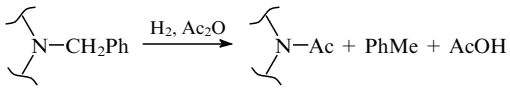
The use of hydrogen peroxide or peroxy acids as oxidants does not result in the target product, defragmentation of the polycyclic cage occurs instead. *N*,*N*′-Dibenzylurea has been isolated as a product of the oxidative decomposition of the hexabenzyl derivative **2a**.[11,16]

In principle, the benzyl groups at the nitrogen atoms can be removed by catalytic hydrogenolysis.

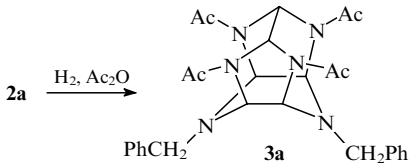


However, the reduction of **2a** with molecular hydrogen at an elevated pressure resulted in the decomposition of the polycyclic cage. The irreversible decomposition proceeds competitively in several directions to yield a mixture of products with both cyclic and linear structures.[17]

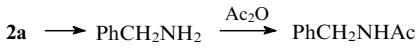
If the reduction is carried out in the presence of an acylation agent, it becomes possible to protect the secondary amino groups generated and thus to reduce the extent of decomposition of the polycyclic cage. As a result, the reductive debenzylation of **2a** can be successfully accomplished to afford the respective acyl derivative. If acetic anhydride is used as the acylation agent, the reaction proceeds stepwise and yields a mixture of various polyacetylpolybenzyl derivatives.[17–19]



2,6,8,12-Tetraacetyl-4,10-dibenzyl-2,4,6,8,10,12-hexaazatetracyclo[5.5.0.0^{3,11}.0^{5,9}]dodecane (**3a**) is the main reaction product, which apparently suggests higher stability of the benzyl groups at the nitrogen atoms of the piperazine ring against debenzylation as compared to other benzyl groups that can be rather easily substituted.



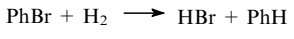
A chromatographic analysis of the reaction mixture revealed at least four by-products, in particular, *N*-benzylacetamide. This implies that the hydrogenation is accompanied by partial decomposition of the polycyclic cage.[18]



N-Benzylacetamide is a catalyst poison and stops the hydrogenation reaction almost completely, which consequently results in a decrease in the yield of the dibenzyl derivative **3a**.[18]

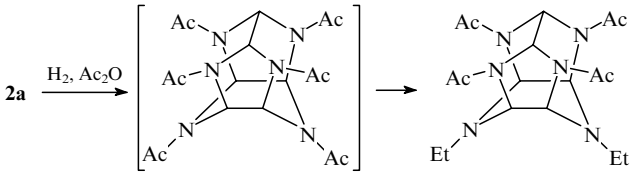
The yield of **3a** also depends on the amount and activity of the hydrogenation catalyst utilised, concentration of acetic anhydride and the nature of the solvent. Typically, hydrogenation is performed in the presence of palladium catalysts supplemented with catalytic amounts of hydrohalide acids.[1,5,19]

The selectivity of the reaction can be substantially enhanced by choosing a proper solvent. For instance, the yield of **3a** was 50% – 65% (with respect to the hexabenzyl derivative **2a**) in acetic anhydride[19] and increased to 75% in a mixture of ethylbenzene with *N*-acetoxysuccinimide and acetic anhydride (20 h, p_{H_2} = 9.8 kPa)[18] and further to 80% in DMF, *N*-methylpyrrolidone or 1,2-dimethoxyethane in the presence of a bromine source (*e.g.*, molecular bromine, bromobenzene or acetyl bromide) and acetic acid (20 – 50 °C, 6 – 12 h).[20] The role of the bromine source is to supply hydrobromic acid, which is necessary to activate the acetylating agent.[20]



According to the kinetic studies of the hydrogenation process, the activation energy is 48 kJ mol^{-1} at a stirring velocity of 2.43×10^6 min^{-1} and a temperature of 30 °C. The rate constant for the first-order reaction is 1.33×10^{-2} min^{-1} (see Ref. 21).

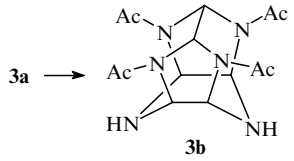
2,6,8,12-Tetraacetyl-4,10-diethyl-2,4,6,8,10,12-hexaazatetracyclo[5.5.0.0^{3,11}.0^{5,9}]dodecane was isolated as the main hydrogenation product of **2a** on a palladium catalyst at a hydrogen pressure of 2942 – 3923 kPa in acetic anhydride containing 10% – 20% of acetic acid.[17]



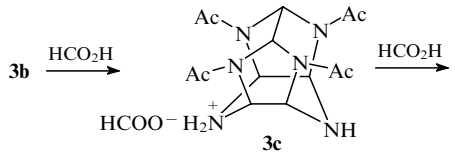
Presumably, the reaction proceeds *via* a hexaazaisowurtzitane hexaacetyl derivative, but this mechanism has not been confirmed. A single reaction intermediate has been isolated by HPLC, most probably, 2,6,8,12-tetraacetyl-4-benzyl-10-ethyl-2,4,6,8,10,12-hexaazatetracyclo[5.5.0.0^{3,11}.0^{5,9}]dodecane.

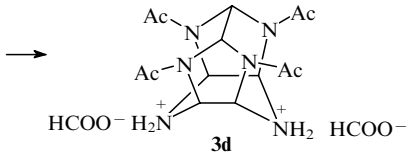
Based on the experimental facts outlined above, one can conclude that debenzylation of **2a** should be carried out in two steps of which the first involves the formation of the dibenzyl derivative **3a** and its isolation from the reaction mixture and the second, removal of the remaining benzyl groups at the nitrogen atoms of the piperazine ring.

The reduction of the dibenzyl derivative **3a** in acetic acid at a hydrogen pressure of 4.53 kPa in the presence of $Pd(OAc)_2$ for 15 h affords 2,6,8,12-tetraacetyl-2,4,6,8,10,12-hexaazatetracyclo[5.5.0.0^{3,11}.0^{5,9}]dodecane (**3b**) in a 73% yield.[18]

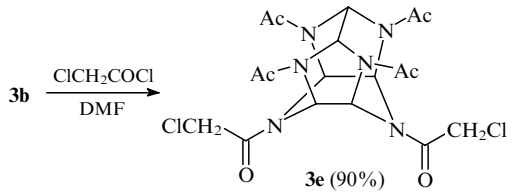


Hydroformates **3c** and **3d** are obtained in solutions of **3b** in formic acid.[22]

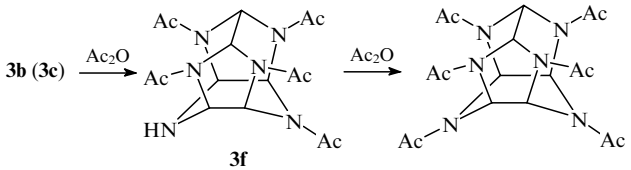




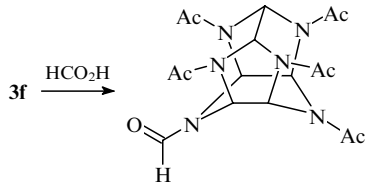
The reaction of the dihydro derivative **3b** with chloroacetyl chloride in DMF yields the respective bis(chloroacetate) **3e**.[23]



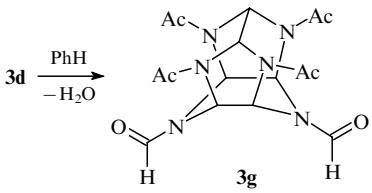
Compound **3b** and its mono(hydroformate) **3c** are converted into 2,4,6,8,12-pentaacetyl-2,4,6,8,10,12-hexaazatetracyclo[5.5.0.0^{3,11}.0^{5,9}]dodecane (**3f**) in the presence of an acylation agent.[24] The synthesis of the hexaacetyl derivative has also been reported.[22] The reaction is performed in the presence of pyridine at 60 °C.



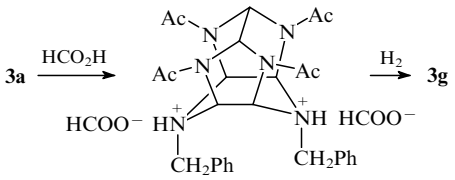
Formylation of the pentaacetyl derivative **3f** yields 2,6,8,10,12-pentaacetyl-4-formyl-2,4,6,8,10,12-hexaazatetracyclo[5.5.0.0^{3,11}.0^{5,9}]dodecane.[24]



2,6,8,12-Tetraacetyl-4,10-diformyl-2,4,6,8,10,12-hexaazatetracyclo[5.5.0.0^{3,11}.0^{5,9}]dodecane (**3g**) was synthesised by the reaction of the bis(hydroformate) **3d** with acetic anhydride in the presence of pyridine or with acetyl chloride.[22] This dehydration reaction also occurs when the salt **3d** is boiled in benzene with azeotropic distillation of water.[15]

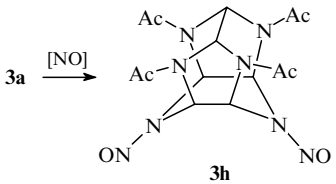


The diformyl derivative **3g** is also formed upon hydrogenation of the dibenzyl derivative **3a** in concentrated formic acid.[18, 22] It was suggested that formic acid plays a prominent role in the process by converting the benzylamine fragment into benzylammonium formate, which undergoes the reduction more easily.



This suggestion on the involvement of protonation is supported by the isolation of the formates **3c** and **3d** from the reaction mixture and by the fact that the activity of the hydrogenation catalyst used for the removal of the two remaining benzyl groups is not critical. Therefore, the catalyst used in the first hydrogenation step (*i.e.*, in the conversion of **2a** into **3a**) can also be used for the preparation of the diformyl derivative **3g** without regeneration.[20, 22] For the synthesis of **3g**, the use of formic acid with a concentration not lower than 88% is preferable. In dilute solutions, the dihydro derivative **3b** or its formates **3c**,**d** can be isolated.[20] The formation of the diformyl derivative **3g** proceeds at a lower rate than that of the dibenzyl derivative **3b** due to lower reactivity of the benzyl groups at the nitrogen atoms of the piperazine ring as compared to the benzyl groups in other positions. The yield of the diformyl derivative **3g** is as high as 86%.[20]

Nitrosation is an established method for the substitution of benzyl groups at nitrogen atoms of secondary amines. Wardle *et al.*[4] adapted this method to the nitrosation of the tertiary amine **3a** containing two benzyl groups and obtained 2,6,8,12-tetraacetyl-4,10-dinitroso-2,4,6,8,10,12-hexaazatetracyclo[5.5.0.0^{3,11}.0^{5,9}]dodecane (**3h**).

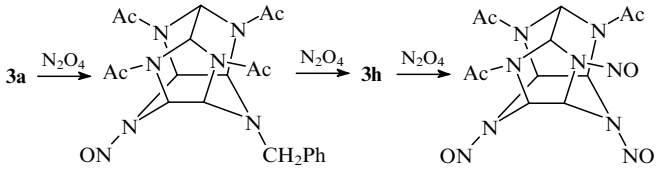


Nitrosonium tetrafluoroborate was used as the nitrosation agent. The reaction was carried out in aqueous sulfolane. The overall process included two steps: first, oxidation of the benzyl groups (to form benzaldehyde) and subsequent nitrosation of the amino groups.[4] The yield of the dinitroso derivative **3h** was 55%. In acetonitrile as the solvent, the yield was lower (10%).[25]

Nitrosation of the dibenzyl derivative **3a** with excess of N_2O_4 at 15–16 °C for 20 h afforded **3h** in 92% yield.[25]

In acetic acid, the reaction is more safe than in pure N_2O_4, but is slower.[26] TLC analysis of the reaction products confirmed the presence of an intermediate, 2,6,8,12-tetraacetyl-10-benzyl-4-nitroso-2,4,6,8,10,12-hexaazatetracyclo[5.5.0.0^{3,11}.0^{5,9}]dodecane. Contamination of the dinitroso derivative **3h** with this intermediate can be avoided by increasing the reaction time and N_2O_4

concentration, but 10% – 12% of another admixture, *viz*., 6,8,12-triacetyl-2,4,10-trinitroso-2,4,6,8,10,12-hexaazatetracyclo-[5.5.0.$0^{3,11}$.$0^{5,9}$]dodecane, is formed. The presence of this admixture substantially lowers the melting point of the product **3h** but does not prevent the next step, *i.e*., nitrolysis.[26]

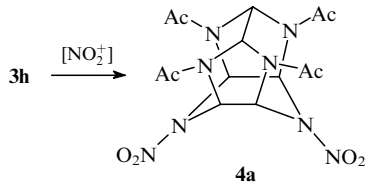


Nitrosation of the dihydro derivative **3b** with sodium nitrite in acetic acid affords the dinitroso derivative **3h** in a yield as high as 95% – 100%.[27]

The tetraacetylhexaazaisowurtzitane derivatives described above are used as the starting materials in the synthesis of HNIW.

IV. Nitrolysis of tetraacetylhexaazaisowurtzitane derivatives

The final step in the synthesis of HNIW is the nitrolysis of tetraacetylhexaazaisowurtzitane derivatives. In general, this is a complex multi-step process, which yields an array of intermediate hexaazaisowurtzitane nitro derivatives, for instance, 2,6,8,12-tetraacetyl-4,10-dinitro-2,4,6,8,10,12-hexaazatetracyclo[5.5.0.$0^{3,11}$.$0^{5,9}$]dodecane (**4a**), which is produced upon partial nitrolysis of **3h**.

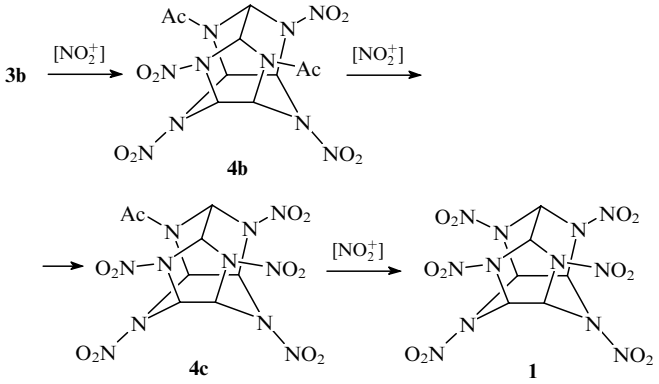


Compound **4a** was synthesised by treating the nitrosation products of the dibenzyl derivative **3a** with nitronium tetrafluoroborate in acetonitrile at 45 °C. The yield of the product **4a** was 59%.[28] The reaction of the dinitroso derivative **3h** with nitric acid at room temperature afforded **4a** in 95% yield.[29]

The target hexanitro derivative can be obtained by nitrolysis of various tetraacetyl derivatives, *viz*., compound **3b**, its mono- (**3c**) and bis(hydroformate) (**3d**), bis(chloroacetyl) (**3e**), diformyl (**3g**), dinitroso (**3h**) and dinitro (**4a**) derivatives.

Nitrolysis of **4a** with nitronium tetrafluoroborate in sulfolane afforded **1** in 90% yield. The yield decreased to 30% if the reaction was carried out in a mixture of sulfuric and nitric acids.[18]

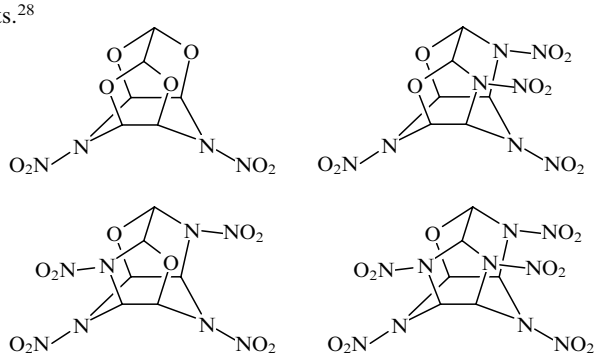
Several authors reported consecutive nitrosation and nitrolysis of the dibenzyl derivative **3a** without isolation of the intermediate dinitroso derivative **3h**. Thus the nitrosation of compound **3a** with nitrosonium tetrafluoroborate in sulfolane followed by nitrolysis of the dinitroso derivative **3h** obtained with nitronium tetrafluoroborate afforded compound **1** in 93% – 97% yield.[4, 8] In another synthesis,[25] compound **3a** was nitrosated with N_2O_4 and then nitrated with a mixture of sulfuric and nitric acids (20 : 80); the yield of HNIW was 97%. A major disadvantage of such one-pot syntheses is the higher explosion hazard due to the presence of benzaldehyde in the reaction mixture after nitrosation, which is nitrated to yield trinitrobenzoic acid.[2] Isolation of the nitrosation product **3h** from the reaction mixture significantly increases safety of the nitrolysis step. The isolated product **3h** is further nitrated with a mixture of sulfuric and nitric acids to give HNIW in 93% yield.[26] As has been established, the conversion of the dinitroso derivative **3h** into HNIW proceeds slowly even in 99% nitric acid and is accompanied by the formation of two by-products, *viz*., 2,8-diacetyl-4,6,10,12-tetranitro- (**4b**) and 2-acetyl-4,6,8,10,12-pentanitro-2,4,6,8,10,12-hexaazatetracyclo[5.5.0.$0^{3,11}$.$0^{5,9}$]dodecane (**4c**). Both intermediates have been isolated chromatographically and their structures have been confirmed by NMR and IR spectroscopy and elemental analysis.[26, 27]



The addition of sulfuric acid (10% – 15%) to the reaction mixture accelerates the reaction substantially. However, the higher rate of the nitrolysis does not guarantee the absence of admixtures in the final product, since sulfuric acid decreases solubility of the intermediates. This results in the co-crystallisation of the intermediates **4b** and **4c** with the target product **1**. If the modulus § is larger than 15, after 2 h the yield of HNIW at 70 – 75 °C is 99% (TLC).[26]

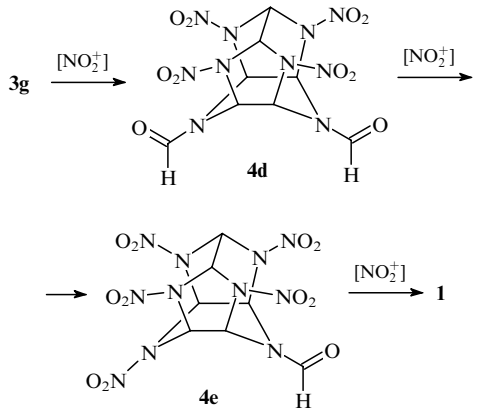
Yet another method for the nitrolysis of the diformyl derivative **3g** has been developed,[28] which makes it possible to prepare **1** in a virtually quantitative yield using 99% nitric acid (with the modulus of 4) in 4 h. Mixtures of sulfuric and nitric acids [29] or nitric acid and ammonium nitrate [30 – 32] can also be used as nitration agents. During the nitrolysis of **3g**, the temperature of the reaction mixture is gradually raised to 75 – 80 °C (*i.e*., the temperature of the reaction onset). The upper temperature limit is determined by the boiling point of the reaction mixture.

The mechanism of the nitrolysis of the diformyl derivative **3g** has not been studied in detail so far. Presumably, concomitantly with consumption of nitric acid present in the nitration mixture water is accumulated, which can induce partial hydrolysis of the hexaazaisowurtzitane cage at an elevated temperature to yield oxatetracyclo[5.5.0.0.$^{3,11}0^{5,9}$]dodecane derivatives as by-products.[28]



Furthermore, products of incomplete nitrolysis of the diformyl derivative **3g**, *viz*., diformyltetranitrohexaazawurtzitane (**4d**) and monoformylpentanitrohexaazawurtzitane (**4e**) derivatives are formed due to insufficiently drastic reaction conditions.[29] Both these products were isolated by preparative chromatography and their structures were confirmed by IR and NMR spectroscopy. The isolation of the intermediates **4d** and **4e** suggests that formyl groups in **3g** are substituted more slowly than the acetyl groups.

§ Hereinafter, the amount of the acid (in g) per 1 g of the substrate is meant.



The incomplete nitrolysis product, *viz*., compound **4e**, is the major by-product in the synthesis of HNIW from the diformyl derivative **3g**.[28,29,32–36] This admixture cannot be efficiently removed by recrystallisation. The complete nitrolysis can only be achieved by prolonged (7–14 h) reaction at high temperature (115–120 °C) (Fig. 1).[31,32] Such modes were realised if mixtures of sulfuric and nitric acids or nitric acid and ammonium nitrate with a modulus smaller than 10 were used as nitration agents. The role of ammonium nitrate consists of stabilisation of the nitration mixture and an increase in its boiling point, which makes it possible to achieve yields of the target product **1** as high as 98%–99% at a contamination level of 1.5%–0.5% (see Fig. 1).[30,32]

Nitration of the dihydro derivative **3b** is faster than that of the diformyl derivative **3g**, but the yield of **1** is smaller in this case (90%).[33] Nitrolysis of **3b** is of interest since HNIW synthesised by this route is free of formyl admixtures, although other by-products can still be present (no intermediates have been isolated so far), which can affect the sensitivity of compound **1** to mechanical actions.[33] The nitrolysis of compound **3b** is a multi-step process. Probably, at the beginning of the reaction, the free amino groups of the substrate **3b** undergo protonation in the acidic solution. Then, the nitrolysis of the AcN fragments occurs, which gives rise to an increase in the concentration of acetic acid in the reaction mixture. Acetic acid reacts with nitric acid to yield acetyl nitrate. Presumably,[33] it is acetyl nitrate, which is the reagent of choice for the nitration of secondary amines, that is involved in the nitration of the NH_2^+ fragments.

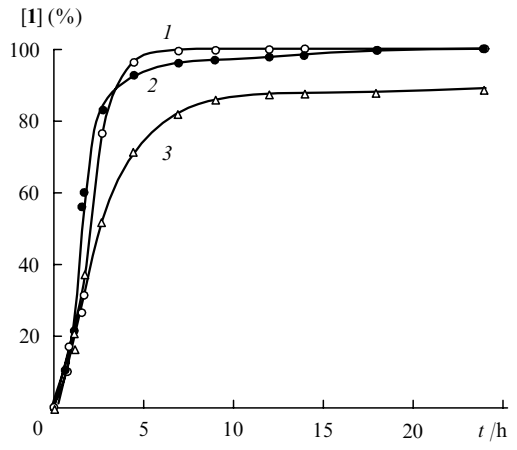


Figure 1. The fraction of hexanitrohexaazaisowurtzitane **1** in the nitrolysis products of the diformyl derivative **3g** as a function of the nitrolysis time and the type of nitration agent.
Nitration agents: a mixture of sulfuric and nitric acids (15 : 85) at a modulus of 5 (*1*); nitric acid–ammonium nitrate (25%) at a modulus of 6 (*2*); 98% nitric acid at a modulus of 5 (*3*).

This simplified scheme is complicated by the nature of the substrate subject to nitration. It is known that the basicity of the nitrogen atoms in polycyclic cage compounds are low. Therefore, unlike the nitration of standard amines that occurs rather smoothly, the nitration in this case is accompanied by partial decomposition of the cage. No oxides are evolved in this process and upon splitting of the acetyl groups in the nitrolysis of compound **3b** in contrast to the nitrolysis of the diformyl derivative **3g**, which is accompanied by the intense gas evolution, probably, owing to the decomposition of the formyl fragments. Thus, one can conclude that the decomposition products of **3b**, which can contain water and stable acidic fragments of the cage, do not undergo oxidation under the nitrolysis conditions.[29] Compound **3b** can be nitrated with an anhydrous mixture of nitric and sulfuric acids (85 : 15) at a modulus of 9 and 83 °C to afford HNIW in 91.8% yield.[33]

The product **1** obtained upon nitration of the chloroacetyl derivative **3e** is contaminated with 4-chloroacetyl-2,6,8,10,12-pentanitro-2,4,6,8,10,12-hexaazatetracyclo[5.5.0.0^{3,11}.0^{5,9}]dodecane.[23]

Thus, the methods based on the use of hexabenzylhexaazaisowurtzitane **2a** as a key compound and various tetraacetyl derivatives **3a**–**h** as intermediates have found the widest application among all methods for the synthesis of hexanitrohexaazaisowurtzitane reported in the literature.[27,29,31,32,35]

V. Polymorphism of hexanitrohexaazawurtzitane and preparation of its ε-polymorph

Under normal conditions, HNIW has four stable polymorph modifications, *viz*., α, β, γ and ε,[4,37,38] which differ from each other in the spatial orientation of the nitro groups relative to the five- and six-membered rings of the cage, the type of the crystal packing and the number of molecules per unit cell (Table 3).[37]

The β polymorph isolated by recrystallisation of crude HNIW from benzene was the first crystalline modification discovered.[4] This modification is the least stable as regards polymorphic transformations: it readily converts into the γ polymorph at 185 °C.[37] The latter can be obtained by the nitrolysis of the diformyl derivative **3g** with nitric acid at a modulus no more than 4.5.[28] Heating of γ HNIW to 230 °C changes the crystal structure. According to data from IR spectroscopy, this is most likely due to a structural modification of the γ HNIW[4] rather than a phase transition into another polymorph form (*e.g*., δ polymorph, as was suggested earlier[37]). The conformations of the HNIW molecules in the β and γ polymorphs are identical, but their packing types are different, which results in different symmetries of their crystal structures [orthorhombic and monoclinic, respectively (see Table 3)].[37]

The α polymorph is formed upon precipitation of HNIW with chloroform from its solutions in sulfolane.[4] Crystalline hemihydrate was obtained upon recrystallisation of this polymorph from 75% nitric acid. The crystal structure of the α polymorph is stabilised by inclusion of water molecules in cavities at the inversion centres of the crystal lattice. The inclusion of a water molecule in each cavity gives rise to the hemihydrate whereas the quarterhydrate is formed if only 50% of all cavities are occupied (see Table 3).[37]

The ε polymorph is characterised by the maximum density and thermal stability among all known crystalline modifications of HNIW. In addition to the modifications listed in Table 3, one more modification, *viz*., the labile δ form, is known. This form, which is stable only at elevated pressures, was detected during the equilibrium transformation of the γ phase. The crystal structure of the δ polymorph and the conformation of the HNIW molecules therein have not been determined so far.[37,39]

Theoretically, 24 conformers of the HNIW molecule with different orientations of six nitro groups relative to the molecular cage are possible. The number of most probable conformations is reduced to nine if sterical hindrance is taken into consideration.

Table 3. Properties of the HNIW polymorphs.

Property	Polymorph			
	α	β	γ	ε
Orientation of the NO_2 groups at the atoms N(4) and N(10)	*exo*,*exo*	*exo*,*exo*	*exo*,*exo*	*exo*,*endo*
Number of molecules per unit cell	8	4	4	4
Space group	*Pbca*	$Pb2_1a$	$P2_1/n$	$P2_1/n$
Symmetry	orthorhombic	orthorhombic	monoclinic	monoclinic
Crystal habitus	prisms	needles	plates	prisms
Decomposition temperature /°C	260	260	260	260
Polymorphic transition temperature (and type) /°C	–	185 (β → γ)	230 (γ → δ)	–
Density /g cm^{-3}	1.961 (2.001) [a]	1.985	1.916	2.04

[a] The value is given for the hemihydrate of the α polymorph.

Presumably, the density of the most symmetrical structure is higher than that of the ε polymorph. However, the high symmetry does not ensure necessarily the stability of the conformer: according to calculations, the ε polymorph is more stable.[37]

Two groups of methods, *viz*., precipitation and evaporation crystallisation, are used for the preparation of HNIW as the ε polymorph.

The technology of precipitation methods implies that a crystallisation seed is first placed into a solution of HNIW in a suitable solvent and then a precipitant is gradually added to the solution.[38,40] The precipitate formed is filtered off and dried. The reverse sequence of steps, *i.e*., addition of a HNIW solution to a precipitant with stirring, is also documented.[41]

Prior to crystallisation, crude HNIW is dissolved in ethyl acetate, and the solution is washed with water or 10% aqueous sodium carbonate (to remove acids) to neutral pH of the aqueous layer, then traces of water are removed by aseotropic distillation with the solvent or using a desiccant, such as anhydrous magnesium sulfate or sodium sulfate.[42]

The solvents for crystallisation where the solubility of HNIW is more than 20% include ethyl acetate or acetone,¶ whereas in precipitants the solubility of HNIW does not exceed 1% (aliphatic and aromatic hydrocarbons: heptane, hexane, benzene, toluene, xylenes, mineral oil or chloroform).[38,42,43] Hexanitrohexaazaisowurtzitane forms crystalline solvates with sulfolane and DMF.[2,44]

An original procedure of the preparation of solutions for the precipitation crystallisation of ε HNIW was proposed by Bescond *et al*.[25] Pre-purified and dried HNIW is repeatedly heated and cooled in a mixture containing 27.5% of poly(glycidyl azide), 35% of trimethylolethane trinitrate, 35% of butane-1,2,4-triol trinitrate, 1.25% of 2-nitrodiphenylamine and 1.25% of *N*-methyl-*p*-nitroaniline. This procedure yields the ε polymorph with a density of ~2.04 g cm^{-3}.

The technology of the evaporation crystallisation is based on the gradual distillation of the solvent from a mixture of HNIW – solvent – precipitant, which favours an increase in the concentration of HNIW and precipitation of the ε polymorph. The solvent used has to be more volatile than the precipitant. Acetone, ethyl acetate, isopropyl acetate, methyl acetate, tetrahydrofuran, acetonitrile and ethyl methyl ketone are typically used as solvents, whereas toluene, dichloroethane or xylene are used as precipitants. Precipitation of the ε polymorph with a certain particle size and granulometric composition can be achieved by adjusting temperature, stirring velocity and distillation rate.[25]

The thermal stabilities of different polymorphs of HNIW and possibilities of the phase transitions have been studied in detail by IR and optical spectroscopy, thermography and manometry.[37,43,45–48] It has been established that the thermal stability of the polymorphs increases in the series β < α < α·H_2O < γ < ε.[37] The process of the thermal decomposition of HNIW in a solid phase follows first-order autocatalytical kinetics. The thermolysis of HNIW and its inflammation are accompanied by the formation of a solid residue.[45] Nitrogen constitutes a half of the gaseous products generated upon thermolysis.

According to tests, the explosion power of compositions based on HNIW is 14% higher than that of analogous octogen-based compositions.[3] Furthermore, the propelling performance (according to the faceplate acceleration tests) of hexanitrohexaazaisowurtzitane is superior to that of octogen. The energy density of HNIW is 8% higher than that of octogen.[3] This indicates that HNIW is currently the most powerful explosive and it will undoubtedly find wide applications in the armaments industry. More details on the sensitivity and thermal stability of HNIW as well as of compositions using its base can be found in a recent review by Nair *et al*.[49]

VI. Conclusion

The analysis of published data indicates that there are several convenient methods for the synthesis of hexanitrohexaazaisowurtzitane. In all cases, hexabenzylhexaazaisowurtzitane **2a** is used as the starting material. The divergence of the synthetic routes begins from the step for the preparation of derivatives suitable for nitrolysis and the conditions of the nitrolysis. The best studied method for the synthesis of hexanitrohexaazaisowurtzitane implemented at the industrial scale is the two-step reductive debenzylation of hexabenzylhexaazaisowurtzitane **2a** to yield the dihydro (**3b**) or diformyl (**3g**) derivatives, which are subsequently nitrated with nitric acid-based systems.

The establishment and development of industrial technologies for the production of HNIW will favour wider utilisation of this highly promising product.

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