Short communication

Synthesis of RDX by nitrolysis of hexamethylenetetramine in fluorous media

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Abstract

Perfluorooctanesulfonic acid ($CF_3(CF_2)_7SO_3H$, PfOS) catalyses the highly efficient nitrolysis of hexamethylenetetramine in fluorous media, affording high yield of explosive RDX. The reaction can be carried out at room temperature in the absence of acetic anhydride and produces smaller amounts of waste acid and nitrate than in traditional process. The fluorous phase containing catalyst could be easily and efficiently recovered for reuse by simple phase separation.
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Keywords: RDX; Hexamethylenetetramine; Perfluorooctanesulfonic acid; Fluorous media

1. Introduction

Nitrolysis is one of the key processes in synthetic chemistry and is widely used industrially [1]. However, traditional nitrolysis is one of the most troublesome functionalizations in the context of green chemistry [2]. Despite some breakthroughs based on the use of various catalyst [3] and the use of $NO^+BF_4{}^-$ [4], N_2O_5/HNO_3 [5], N_2O_5/halobenzenes [5], $N_2O_5/(CF_3CO)_2O$ [5], $N_2O_5/(CF_3SO_2)_2O$ [5], as a nitrolysis agent, major problems remain especially when nitrolysis is required for the production of energetic materials.

RDX, named hexahydro-1,3,5-trinitro-1,3,5-triazine or cyclotrimethylenetrinitramine, a high explosive energetic material, plays an important role in defence industry in many countries [3]. In the conventional process for making RDX, hexamethylenetetramine is treated with 98–100% nitric acid in the presence or absence of ammonium nitrate (NH_4NO_3) [6,7]. The procedure required large excess of nitric acid (20–24 eq.) and ammonium nitrate (12–14 eq.) with the plague of waste acid, nitrate and by-products resulting from oxidation at elevated temperature. Although smaller amounts of nitric acid (4–5 eq.) and ammonium nitrate (3–4 eq.) were required in acetic anhy-

dride containing process [8], use of 6–8 eq. of acetic anhydride produces considerable added expense.

Inspired by the recent work on the polynitration [9] in the presence of perfluorooctanesulfonic acid, a strong monobasic acid with an acidity function H_0 being -12.08 (that of sulfuric acid is -11.90) [10] and especially solubility in fluorous solvents (perfluorocarbons, PFC) [9,11], we have applied the catalytic system PfOS–PFC to the nitrolysis of hexamethylenetetramine. It was exciting to find that rather high yield of the high explosive RDX and the robustness of the catalytic system for recycling using by simple phase separation were obtained. We would like to report herein the work on this new application of the catalytic system.

2. Experimental

2.1. General remarks

Melting points were obtained with Shimadzu DSC-50 thermal analyzer. ^{19}F NMR spectra were characterized with a Bruker Advance RX300 spectrometer. IR spectra were recorded on a Bomen MB154S infrared analyzer. UV–vis spectra were obtained with a UV-1601 apparatus. Mass spectra were recorded on a Saturn 2000GC/MS instrument. Elemental analyses were performed on a Yanagimoto MT3CHN recorder. Perfluorooctanesulfonic acid was commercially obtained from ARCOS Co. All fluorous solvents were purchased from Aldrich Co.

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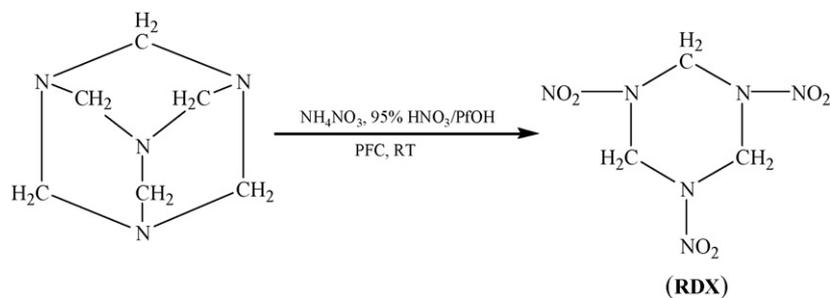
Scheme 1. Nitrolysis of hexamethylenetetramine in fluorous media.

Commercially available reagents were used without further purification.

2.2. Typical procedure for nitrolysis in fluorous media

Hexamethylenetetramine (0.49 g, 3.5 mmol) was added to a mixture of PfOS (0.18 g, 0.35 mmol) and perfluorodecalin ($C_{10}F_{18}$, *cis* and *trans*-mixture, 15 ml) in a glass flask under vigorous stirring. After 10 min, a solution of 95% HNO_3 (1.4 ml, 35 mmol) containing ammonium nitrate (0.14 g, 1.75 mmol) was introduced into the flask within 15 min at room temperature. The mixture was stirred at room temperature for 6 h, and then was filtered. The solid obtained was washed with warm water (10 ml), and dried to give a white product (0.98 g, 125.8%) with a m.p. of 202–203 °C. When the product was stirred with 55% HNO_3 (5 ml) at 70 °C for 1 h, cooled and filtered, a 96% recovery of RDX (0.94 g, based on the crude product) with a m.p. of 205–206 °C (literature [8] 205–206 °C) was obtained. IR spectra of the product are identical with the authentic sample. Anal. calcd. for $C_3H_6N_6O_6$: C, 16.22; H, 2.70; N, 37.84. Found: C, 16.21; H, 2.74; N, 37.81.

2.3. Typical procedure for catalyst recycling

After the reaction as described above, the filtrate from the reaction mixture was allowed to stand for *ca.* 1 h without stirring at room temperature, and the water phase on the top layer was separated using a pipette. The resulting fluorous phase was ready for further runs: that is, hexamethylenetetramine (0.49 g, 3.5 mmol), ammonium nitrate (0.14 g, 1.75 mmol) in 95% HNO_3 (1.4 ml, 35 mmol) were added to the fluorous phase. The mixture was stirred at room temperature.

2.4. Typical procedure for the test of leaching and catalyst recovery

The above mentioned water phase was shaken with hot $CF_3C_6H_5$ (5 ml, 40–60 °C), and the $CF_3C_6H_5$ layer was separated. An aliquot (0.8 μl) was analyzed by GC–MS equipped with a FID. Injection port temperature is 250 °C; detector temperature is 270 °C; carrier gas is nitrogen. The recycled fluorous phase was evaporated under reduced press to remove and recover perfluorodecalin. The residue (PfOS) was analyzed by UV–vis or ^{19}F NMR. In the measurement of UV–vis, pure water (10 ml) was added to the residue and an aliquot (4 ml) was conducted on

a UV-apparatus. In the measurement of ^{19}F NMR, a solution of C_6F_6 (0.0814 g, 0.438 mmol) in $CF_3C_6H_5$ (15 ml) was prepared. The residue was dissolved in the solution for NMR analysis; ^{19}F NMR (300 MHz, $CF_3C_6H_5$): δ −80.9 (CF_3), −112.7 (α-CF_3), −119.8 (β-CF_3), −121.1 (γ-CF_3), 122.4 (3x–CF_2–), 125.8 (θ-CF_3). The total intensities of all $(CF_2)_7CF_3$-based CF_3 triplets were integrated against the C_6F_6 signal.

3. Results and discussion

The nitrolysis of hexamethylenetetramine was carried out in perfluorodecalin using 95% nitric acid as a nitrolysis agent (Scheme 1). In the reaction, our efforts here were directed toward the reduction of nitric acid and ammonium nitrate consumed. The results were summarized in Table 1. The reaction using nitric acid alone did not give significant conversion to RDX even in the presence of excess acid (20 eq.) and ammonium nitrate (0.2–0.5 eq.). However, the use of PfOS resulted in moderate yield of RDX at room temperature, which indicates that the presence of PfOS is essential to obtain good yields of nitrolysis. Notably, the system containing 10 mol% PfOS and 0.5 eq. of ammonium nitrate with 10 eq. of nitric acid gave the RDX in 125.8% at room temperature after 6 h. Compared with the conventional process, the reaction produces much smaller amounts of waste acid and nitrate. Decrease of nitric acid resulted in much lower yield of RDX. Increase of PfOS and ammonium nitrate appeared not to work for the improvement of nitrolysis.

Table 1
Nitrolysis of hexamethylenetetramine in perfluorodecalin[a]

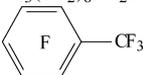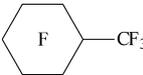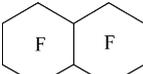| Entry	HNO_3 (eq.)	NH_4NO_3 (eq.)	PfOS (mol%)	Time (h)	Yield (%)[b]
1	10	–	–	8	7.6
2	10	0.2	–	8	13.8
3	20	0.5	–	10	20.3
4	8	0.5	2	6	78.9
5	8	0.5	5	6	104.6
6	10	0.5	10	6	125.8
7	8	0.5	10	6	108.5
8	5	0.5	10	6	70.3
7	10	0.5	15	6	125.1
8	15	0.8	10	6	120.2
9	15	0.8	15	6	119.7

[a] The reaction conditions: hexamethylenetetramine, 3.5 mmol; perfluorodecalin 15 ml; room temperature.
[b] Isolated yields calculated on the basis of 1 mol of RDX per mole of hexamethylenetetramine.

When the reaction was finished, the reaction mixture was filtered and the filtrate was allowed to stand for *ca.* 1 h at room temperature. The fluorous phase with PfOS catalyst can separate from the water phase and return to the bottom layer. Use of fluorous phase, recycled without purification was equally effective, furnishing the RDX product with 125.8, 122.3, 119.4% yields. The problem on leaching in these catalyst recycling systems was studied. Based on GC–MS data, no loss of fluorous solvent perfluorodecalin to the water phases can be detected. There is an absorbance observed for PfOS at around 230 nm on a UV–vis apparatus that can be used as the reference signal for qualitative and quantitative measurements. According to the previous report, all compounds of the formula $X(CF_2)_7CF_3$ give essentially the same CF_3 NMR chemical shift [12]. Hence, the "total number of leached pony tails" can be quite sensitively determined by this method [12]. The measurements of ^{19}F NMR and UV–vis showed that no significant signals for PfOS leaching to the water phase was found. Such results are in accordance with the cases of polynitration [9]. In fact, we also investigated the exact amount PfOS in the recovered fluorous phase by ^{19}F NMR and UV–vis, finding that 99.9% of catalyst retained in perfluorodecalin. This result suggests the robustness of the catalytic system for recycled use. But we found that the loss of PfOS leaching to the water phase become obvious when the volume ratio of fluorous phase to water phase decreased. The results of ^{19}F NMR and UV–vis showed that the loss of PfOS increased from 0.1 to 8.9% with the ratio mentioned above decreasing from 10:1 to 1:1. Thus, controlling high volume ratio of fluorous phase to water phase is an important strategy for the use of this novel catalytic system in nitrolysis.
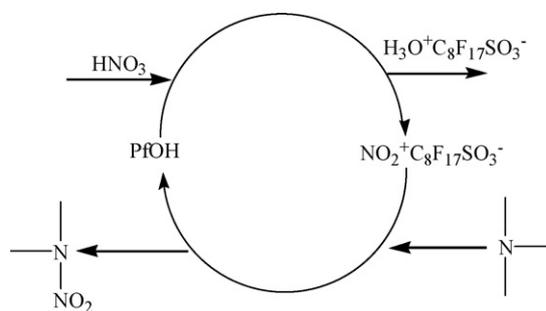
Various fluorous solvents were investigated for the nitrolysis (Scheme 1). As show in Table 2, lower yields were found in perfluorohexane (C_6F_{14}), perfluorooctane (C_8F_{18}) and perfluorooctyl bromide ($C_8F_{17}Br$). When using perfluorotoluene (C_7F_8) and perfluoromethylcyclohexane (C_7F_{14}), the nitrolysis also proceeded smoothly to give desired product in 125.6

Scheme 2. The assumed mechanism for PfOS–PFC catalyzed nitrolysis.

and 124.3% yield, respectively. However, perfluorotoluene was found to be contaminated easily by some unknown organic compounds resulting from the side-reaction in nitrolysis, leading to the poor efficiency on catalyst recycling. The loss of fluorous solvents is significant in the reaction of perfluomethylcyclohexane because it is very volatile (b.p. 76 °C). Therefore, perfluorodecalin is the best fluorous solvent found for the nitrolysis.

The mechanism for PfOS–PFC catalyzed nitrolysis was discussed. Chapman et al. [13] reported that protonitronium $NO_2^+CF_3SO_3^-$ derived from nitric acid and trifluoromethanesulfonic acid (CF_3SO_3H) was an efficient nitrolysis agent. With this powerful reagent, even highly deactivated amides, such as nosylamide containing the most electronegative protecting group to date, can be directly nitrolyzed to the corresponding nitramine in high yield. Thus, in our research the assumed catalytic cycle was shown in Scheme 2. A key nitrolysis agent is proposed to be nitroperflate $NO_2^+C_8F_{17}SO_3^-$, which possesses more strong nitrolysis ability because of eletrodrawing of fluorous tail '$CF_3(CF_2)_7$' that strengthens the electrophilicity of NO_2^+. The nitroperflate $NO_2^+C_8F_{17}SO_3^-$ reacts with amides to afford the corresponding nitramine accompanied by regeneration of PfOS. On the other hand, mechanism research for synthesis of RDX by nitrolysis of hexamethylenetetramine is rather complicated and challenging work. Ammonium nitrate in PfOS–PFC catalyzed process was assumed to play two important roles: contribution partly to amino nitrogen in RDX molecules and hindrance of side-reaction derived from the concentrated nitric acid. As to PFC, it only served as a solvent for dissolving catalyst? It is not sure! Recently, many researchers reported that fluorous solvents are suitable for those exothermic reactions because they can be used as obstructors for thermal transmission [14], which is the essential in the synthesis of RDX by nitrolysis of hexamethylenetetramine [8]. Finally, the possible role of PfOS as an emulsifying agent in microemulsion system was proposed. Microemulsion is a well-known reaction system for the nitration because of its extremely large interfacial areas [15]. PfOS is an emulsifying agent with high surfactancy and chemical stability [16]. In the nitrolysis process, there may be the formation of some kind of microemulsion derived from fluorous phase and water phase [17]. Thus, we think PfOS maybe act as both catalyst and surfactant for the highly efficient nitrolysis reaction.

Table 2
Nitrolysis of hexamethylenetetramine in various fluorous solvents[a]

Entry	PFC	Yield (%)[b]
1	$CF_3(CF_2)_4CF_3$	114.5
2	$CF_3(CF_2)_6CF_3$	115.8
3	$CF_3(CF_2)_6CF_2Br$	112.0
4	F—⟨⟩—CF_3	125.6
5	F—⟨⟩—CF_3	124.3
6	F—⟨⟩⟨⟩—F	125.8

[a] The reaction conditions: hexamethylenetetramine, 3.5 mmol; 95% nitric acid, 10 eq.; ammonium nitrate, 1.75 mmol; PfOS, 10 mol%; PFC, 15 ml; 6 h; room temperature.

[b] Isolated yields calculated on the basis of 1 mol of RDX per mole of hexamethylenetetramine.

4. Conclusions

The PfOS–PFC system can be considered as the most attractive alternative to existing method for preparation of RDX by nitric acid nitrolysis of hexamethylenetetramine. The advantages of our catalytic system over others are: the reaction can be performed at room temperature in the presence of catalytic amount of PfOS without acetic anhydride (1), the process produces much smaller amounts of waste acid and nitrate than in traditional process (2), the fluorous phase containing catalyst is easily separated and can be reused several times without a significant loss of yield of reaction (3). Further investigations of more favourable synthetic conditions and mechanism for nitrolysis, as well as synthetic applications, are currently in progress and will be reported in due course.

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