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Energetic Materials

Synthesis of an Energetic Nitrate Ester**

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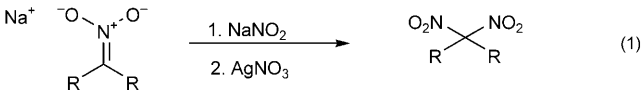
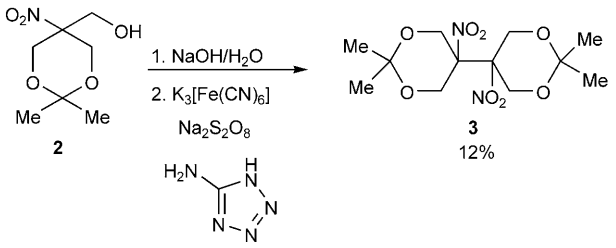
Nitrate esters have been known as useful energetic materials since the discovery of nitroglycerin by Ascanio Sobrero in 1846.[1] The development of methods to increase the safety and utility of nitroglycerin by Alfred Nobel led to the revolutionary improvement in the use of nitroglycerin, in the form of dynamite, in explosive applications. Since then, many nitrate esters have been prepared and incorporated into military applications such as double-based propellants, detonators, and as energetic plasticizers.[2–4] Nitrate esters have also been shown to have vasodilatory effects in humans and thus have been studied and used for treatments of ailments such as angina. The mechanism of the biological response towards nitrate esters has been elucidated recently.[5] Interestingly, many of the nitrate esters used for military purposes are liquids (ethylene glycol dinitrate, propylene glycol dinitrate, etc). Pentaerythritol tetranitrate (PETN) is one of the only solid nitrate esters, besides nitrocellulose, that is used in explosive applications. Unfortunately, the melting point of PETN is above 100 °C, and thus PETN must be pressed as a solid for use in detonator applications. A more practical material would be a melt-castable explosive, which would allow the simplification of manufacturing processes. Herein we describe the synthesis of a new energetic nitrate ester **1** that is a solid at ambient temperature, has a melting point range of 85–86 °C, and has the highest density of any known nitrate ester composed of only carbon, hydrogen, nitrogen, and oxygen. We also describe the chemical, thermal, and sensitivity properties of **1**, as well as some preliminary explosive performance data.

As part of our efforts to develop new energetic materials, we became interested in employing the Kaplan–Shechter[6–8] reaction to construct novel energetic *gem*-substituted nitro-N-heterocyclic moieties. The Kaplan–Shechter reaction is one of the most convenient methods for the synthesis of molecules containing *gem*-dinitro substituents, and involves the treatment of a nitronate salt with nitrite ions in the presence of an oxidant, such as silver nitrate [Eq. (1)].



(1)

Our original goal was to use nitro-compound **2** as a substrate for oxidative coupling reactions with heterocyclic nucleophiles, such as 5-aminotetrazole (Scheme 1). We investigated the modified Kaplan–Shechter[7,8] reaction as a method to reach this target. The reaction conditions involve



Scheme 1. Attempted oxidative coupling reaction.

deformylation of **2** by treatment with hydroxide in the presence of potassium ferricyanide and sodium persulfate, followed by addition of 5-aminotetrazole. The overall result was the production of a white precipitate in low yield. ^{1}H NMR spectroscopy showed that no coupling had occurred between **2** and 5-aminotetrazole. Instead, homocoupling of the nitronate salt of **2** appeared to have taken place, albeit inefficiently (12 % yield), to provide **3**. The homocoupling of nitronate salts has previously been reported,[9] although the use of **3** as a homocoupling substrate under the modified Kaplan–Shechter conditions has not been reported.

Alternative methods for the synthesis of **3** have been reported and include homocoupling of the 5-bromo-5-nitro derivative of **2** in the presence of *tert*-butyl thiol,[10] and the use of an $S_{RN}1$ substitution reaction to provide the product in 30–50 % yield.[11–13] Other methods have also been reported.[14,15]

During the examination of the homocoupled product, we reasoned that it would be possible to hydrolyze the dimethyl ketal protecting group to access the tetraol product **4**, which has not been reported to date. The novel nitrate ester molecule **1** can then be accessed by exhaustive further nitration of the tetraol **4** (Scheme 2). However, for the method to be feasible, a dramatic improvement in the yield of the oxidative coupling step was needed.

Starting from the commercially available dioxane **2**, we studied the effects of concentration, oxidizer, and nitronate formation on the yield of **3**. The amount of the potassium ferricyanide catalyst was also varied. Interestingly, we found that increasing amounts of potassium ferricyanide led to reduction in the yield of the homocoupled product **3**, whereas the yield of **3** increased in the absence of the catalyst. After

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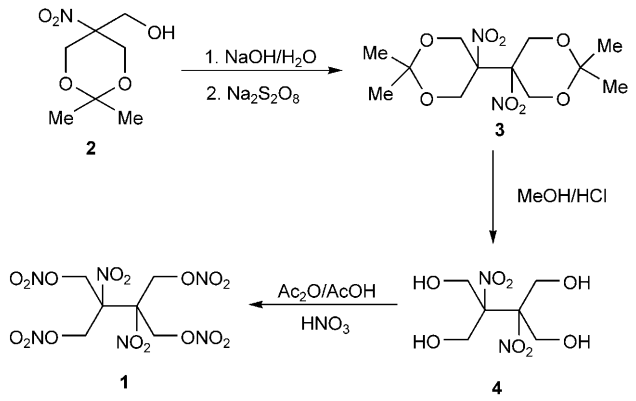

Scheme 2. Synthesis of **1**.

optimization of temperature, concentration, and number of equivalents of base, we were able to improve the yield of the homocoupled product to 65%.

With an improved method for the preparation of **3** in hand, we turned our attention to the remaining two steps. Ketal deprotection was easily accomplished using methanolic HCl. Removal of the solvent led to **4** in good yield (85%). The nitration of the tetraol was found to proceed smoothly in the presence of acetyl nitrate in acetic acid to provide the corresponding tetranitrate ester **1** in 85% yield.

Compound **1** was characterized spectroscopically and thermally. The material begins to decompose at 141 °C with a decomposition energy release of 1818 J g^{-1}. Interestingly, the material has a melting point range of 85–86 °C. This property may allow the material to be used in melt-castable explosives applications. The heat of formation was measured to be −371 kJ mol^{-1} by combustion calorimetry using a Parr 6300 bomb calorimeter. The tetranitrate ester **1** can be recrystallized from a variety of solvents, and large hexagonal crystals can be obtained from ethanol. A digital photograph of the crystal morphology is shown in Figure 1.

X-ray crystallography was used to determine the crystal density of **1**.[16] A colorless thin plate of dimensions 0.40 × 0.10 × 0.02 mm^2 was mounted on a MiteGen MicroMesh using a small amount of Exxon Paratone-N Oil. Data were collected using a Bruker three-circle platform diffractometer equipped with a SMART APEX II CCD detector. The crystal structure of **1** is shown in Figure 2. The crystal density was determined to be 1.917 g cm^{-3}, which makes **1** the most dense nitrate ester to date (Figure 2). Comparison of the bond distances and bond angles with those of PETN[17] show that the C2A–O2A

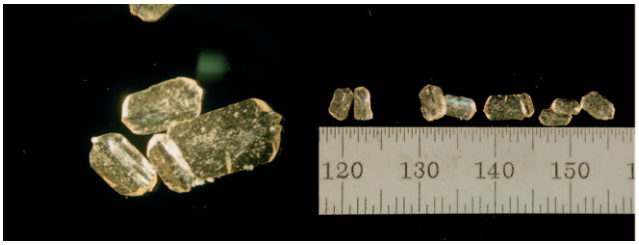

Figure 1. Photographs of crystals of **1** displaying the crystal morphology of crystals grown from ethanol. The ruler scale is in mm.

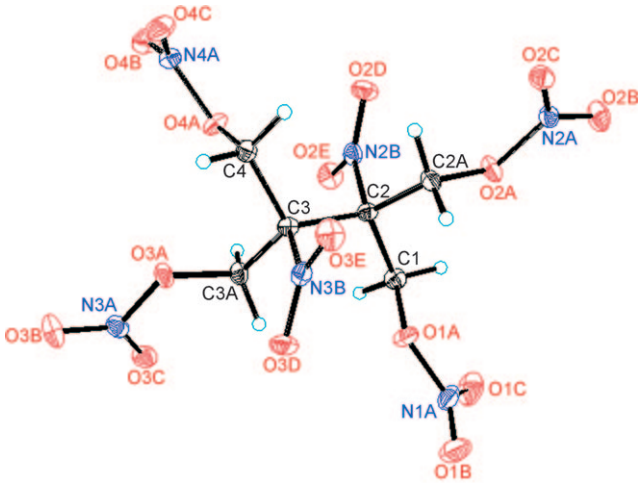

Figure 2. Thermal ellipsoid plot of **1**. Crystals were grown from ethanol by slow evaporation. Thermal ellipsoids are shown at the 50% probability level.

and the O2A–N2A bond lengths are slightly longer in **1** compared to the corresponding distances in PETN. Additionally, the C2-C2A-O2A and the C2A-O2A-N2A angles are smaller in **1** than in PETN.

The sensitivity of material **1** towards destructive stimuli, such as impact, spark, and, friction was also investigated. It was determined that the sensitivity properties of **1** were very similar to those of pentaerythritol tetranitrate (see Table 1).

Table 1: Sensitivity properties of **1**.

	Impact[a]	Spark[b]	Friction[c]	DSC[d]
1	2.7 J	0.625 J	74.5 N	140 °C
PETN	2.9 J	0.625 J	56.8 N	160 °C

[a] LANL type 12, 50% drop height, 2.5 kg. [b] ABL spark threshold initiation level (TIL). [c] 50% load Bruceton up/down method. [d] 10 °C ramp rate.

Explosive performance calculations were performed with the CHEETAH thermochemical code,[18] using the experimental crystal density and measured heat of formation value as the input data. As displayed in Table 2, the performance of **1** is predicted to be equal to that of HMX, a well-characterized high-performance explosive. Unlike HMX however, nitrate ester **1** has a low melting point, which may provide a unique opportunity for melt-castable explosive components. Additionally, **1** offers the possibility of use as a high-energy plasticizer or double-base propellant ingredient. Further experiments are under way to fully characterize the explosive performance and properties of this novel nitrate

Table 2: Predicted performance properties of **1**.

	$V_{Det.}$ [km s^{-1}]	P_{CJ} [GPa]
1[a]	9.1	40
HMX[b]	9.1	39

[a] Cheetah 5.0 calculation. [b] Livermore Explosives Handbook.

ester. Additionally, compound **4** can serve as a synthon for new energetic materials and we are currently investigating the synthetic utility of **4**.

Experimental Section

Caution! Although no problems have occurred during the synthesis and handling of 1, the material is an explosive. Laboratories and personnel should be properly grounded and safety equipment such as Kevlar gloves, blast shields, and ear plugs are necessary, especially when working with large-scale reactions.

3: Compound **2** (76.4 g, 0.40 mol) was added to a solution of sodium hydroxide (32 g, 0.80 mol) in water (1 L) in a jacketed flask at 20 °C. The reaction mixture was heated at 60 °C for 1 h then cooled to 20 °C. Solid sodium persulfate (190 g, 0.80 mol) was added to the reaction mixture and the mixture allowed to stir for 20 h while maintaining the reaction at 20 °C. During this time a white precipitate of **3** formed. The reaction mixture was then adjusted to pH > 11, filtered, washed with cold water, and air dried to give 41.6 g of **3** (65 %). The product was identical in all respects to that previously reported.[11,12]

4: Compound **3** (25.6 g, 0.08 mol) was added to methanol (240 mL). The reaction mixture was stirred while HCl gas was bubbled into the reaction mixture. When dissolution was complete, the HCl addition was stopped, the reaction vessel was stoppered, and the reaction mixture stirred for 48 h. During this time, the color of the reaction mixture turned from amber to dark brown. The volatile components were then removed and the residue was triturated with warm chloroform and filtered to provide 8.1 g of **4** (85 %). M.p. 100–102 °C; IR (KBr): $\tilde{\nu}$ = 3596, 3284, 2975, 2913, 2888, 1482, 1463, 1408, 1385, 1341, 1303, 1255, 1230, 1159, 1135, 1069, 1035, 994, 930 cm^{-1}; ^1H NMR (CD_3CN, 300 MHz): δ = 3.35 (br s, 4H), 4.22 ppm (m, 8H); ^{13}C NMR (CD_3CN, 100 MHz): δ = 61.18, 96.38 ppm. Elemental analysis calcd for $C_6H_{12}N_2O_8$: C 30.01, H 5.04, N 11.66; found: C 30.38, H 5.29, N 11.35.

1: Acetic acid (50 mL) and acetic anhydride (50 mL) were added to a 200 mL jacketed flask. The solution was then cooled to 0 °C and HNO_3 (34 g, 98 %) was added dropwise while maintaining the reaction temperature below 5 °C. The reaction was allowed to stir for 20 min and **4** (12 g, 0.05 mol) was added portionwise. After stirring the mixture for 2 h at 0 °C, the temperature was raised to 20 °C over 1 h and then stirred at 20 °C for 1 h. The reaction mixture was then poured into 200 mL of ice–water and stirred. The white solid was filtered, washed with water, and air dried to give of crude **1** (20 g). This material was then recrystallized from isopropanol to give 18 g of **1** (85 %). M.p. 85–86 °C; IR (KBr): $\tilde{\nu}$ = 3045, 3028, 2982, 2927, 1658, 1583, 1491, 1465, 1450, 1390, 1371, 1334, 1287, 1156, 1099, 1056, 1022, 995, 898, 854 cm^{-1}; ^1H NMR ($CDCl_3$, 300 MHz): δ = 5.6 ppm (s, 8H); ^{13}C NMR ($CDCl_3$, 100 MHz) δ = 68.57, 90.73 ppm. Elemental analysis calcd for $C_6H_8N_6O_{16}$: C 17.15, H 1.92, N 20.00; found: C 17.48, H 2.20, N 19.86.

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[1] T. L. Davis, *Chemistry of Powder and Explosives*, *Coll. Vol.*, Angriff Press, Hollywood, CA, **1943**, (reprinted 1991).
[2] J. P. Agrawal, R. D. Hodgson, *Organic Chemistry of Explosives*, Wiley, Chichester, West Sussex, **2007**.
[3] T. Urbanski, *Chemistry and Technology of Explosives*, *Vol. 2*, Pergamon, Oxford, **1965**.
[4] D. M. Badgujar, M. B. Talawar, S. N. Asthana, P. P. Mahulikar, *J. Hazard. Mater.* **2008**, *151*, 289.
[5] L. J. Ignarro, *Proc. Natl. Acad. Sci. USA* **2002**, *99*, 7816.
[6] R. B. Kaplan, H. Shechter, *J. Am. Chem. Soc.* **1961**, *83*, 3535.
[7] L. C. Lee, V. Grakauskas, K. Baum, *J. Org. Chem.* **1985**, *50*, 1699.
[8] N. Kornblum, H. K. Singh, W. J. Kelly, *J. Org. Chem.* **1983**, *48*, 332.
[9] H. Shechter, R. B. Kaplan, *J. Am. Chem. Soc.* **1953**, *75*, 3980.
[10] A. Amrollah-Madjdabadi, R. Beugelmans, A. Lechevallier, *Tetrahedron Lett.* **1987**, *28*, 4525.
[11] R. Beugelmans, A. Amrollah-Madjdabadi, T. Gharbaoui, A. Lechevallier, *J. Chem. Soc. Perkin Trans. 1* **1995**, *6*, 609.
[12] P. Vanelle, J. Maldonado, M. P. Crozet, K. Senouki, P. Timon-David, *Eur. J. Med. Chem.* **1991**, *26*, 709.
[13] M. P. Crozet, G. Archaimbault, P. Vanelle, R. Nouguier, *Tetrahedron Lett.* **1985**, *26*, 5133.
[14] M. Senkus, US 2543472, **1951**.
[15] H. Piotrowska, M. Poplawska, *Bull. Acad. Pol. Sci. Ser. Sci. Chim.* **1981**, *29*, 335.
[16] Crystal data for **1** : $C_6H_8N_6O_{16}$, M_r = 420.18, monoclinic, $P2_1/n$, a = 8.1228(6), b = 23.0560(16), c = 8.5072(6) Å, α = 90, β = 113.9530(10)°, γ = 90°, V = 1456.01(18) $Å^3$, Z = 4, ρ_{calcd} = 1.917 $Mg\,m^{-3}$, μ = 0.195 mm^{-1}, $F(000)$ = 856, R_1 = 0.0412 for 2382 observed ($I > 2\sigma I$) reflections and 0.0743 for all 3593 reflections, GOF = 0.977, 253 parameters. The crystals were irradiated using graphite monochromated $Mo_{K\alpha}$ radiation (λ = 0.71073). An MSC X-Stream low-temperature device was used to keep the crystals at a constant −170 °C during data collection. Data collection was performed and the unit cell was initially refined using SMART [v5.625] (Bruker (2001a). SMART v5.625. Bruker AXS Inc., Madison, Wisconsin, USA). Data Reduction was performed using SAINT [v6.36A] (Bruker (2002). SAINT v6.36A. Bruker AXS Inc., Madison, Wisconsin, USA) and XPREP [v6.12] (Bruker (2001b). XPREP v6.12. Bruker AXS Inc., Madison, Wisconsin, USA). Corrections were applied for Lorentz, polarization, and absorption effects using SADABS [v2.03] (Bruker (2000). SADABS v2.03, Bruker AXS Inc., Madison, Wisconsin, USA). The structure was solved and refined with the aid of the programs in the SHELXTL-plus [v6.10] system of programs (Bruker (2000). SHELXTL v6.10. Bruker AXS Inc., Madison, Wisconsin, USA). The full-matrix least-squares refinement on F^2 included atomic coordinates and anisotropic thermal parameters for all non-hydrogen atoms. The hydrogen atoms were included using a riding model. CCDC 694822 contains the supplementary crystallographic data for this paper. These data can be obtained free of charge from The Cambridge Crystallographic Data Centre via www.ccdc.cam.ac.uk/data_request/cif.
[17] H. H. Cady, A. C. Larson, *Acta Crystallogr. Sect. B* **1975**, *31*, 1864.
[18] S. Bastea, L. E. Fried, K. R. Glaesemann, W. M. Howard, P. C. Souers, P. A. Vitello, Cheetah 5.0, User's Manual, Lawrence Livermore National Laboratory, **2006**.

