

CrossMark
click for updatesCite this: *RSC Adv.*, 2017, 7, 3617Received 30th October 2016
Accepted 26th November 2016

DOI: 10.1039/c6ra26032b

www.rsc.org/advances

Structures and properties of energetic cations in energetic salts

W. Liu,^a W. L. Liu^a and S. P. Pang^{*b}

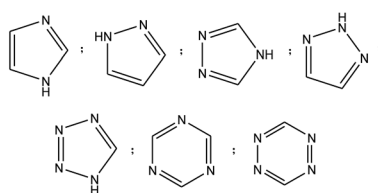
Energetic salts provide many advantages over conventional energetic molecular compounds. Their high densities, high heats of formation and low vapor pressures make them an important class of compounds for the development of energetic materials. More and more novel energetic ions are being obtained, but energetic cations are reported to a much lesser extent. Energetic cations develop from simple linear structures to form N-heterocyclic structures. Together with the introduction of various energetic groups, the energetic properties of energetic salts are significantly promoted. The development of energetic cations is becoming the major restriction for improving the performance of energetic salts.

1. Introduction

In the pursuit of high performance energetic materials, nitrogen-rich heterocyclic compounds have received significant attention.^{1–8} Subsequently, energetic salts have developed to be an important class of high-nitrogen content compounds as a result of their excellent properties, such as low vapor pressures, high densities and high thermal stabilities.^{9–13} In addition, nitrogen-rich heterocyclic ring compounds possess high heats of formation and their low carbon contents make it easier to achieve oxygen balance. To construct the energetic salts, nitrogen-rich heterocyclic compounds are always modified into energetic cations/anions. The typical compounds used for constructing such energetic salts usually include imidazole, pyrazole, 1,2,4-triazole, 1,2,3-triazole, tetrazole, triazine, tetrazine and so on (Scheme 1).

Energetic salts consist of cations and anions, where the cations act as fuels and the anions act as oxidizers. Various

energetic groups can be introduced into the nitrogen-rich heterocyclic rings, which makes the compounds exhibit different acidities/alkalities in becoming energetic cation/anion substrates. Oxygen-rich groups (*e.g.* $-\text{NO}_2$, $-\text{NHNO}_2$, $-(\text{NO}_2)_3$ and $-\text{OH}$) and high heats of formation groups (*e.g.* $-\text{N}_3$) are electrophilic, whose introduction can turn the compounds into energetic anion bases, which could promote the oxidizing ability of the anions. While alkyl and amino groups (*e.g.* $-\text{NH}_2$) are electron-rich, whose introduction can make the compounds energetic cation bases. Alkyl groups are useful for lowering melting points while amino groups are significant for lowering the sensitivities of energetic compounds. Therefore, energetic cations play important roles in determining the performance of energetic salts (Fig. 1). However, with a lack of oxygen in the substituted groups, energetic cations possess lower densities and worse oxygen balance than energetic anions. Meanwhile, compared with energetic anions, energetic cations are reported less frequently, and most energetic cations are amino-substituted



Scheme 1 The N-heterocyclic bases used for constructing energetic salts.

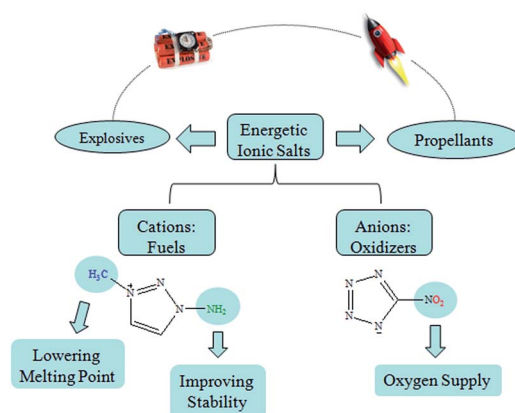
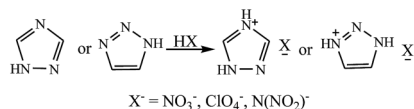


Fig. 1 The roles of cations and anions in energetic salts.

^aBeijing Center for Physical and Chemical Analysis, Beijing Key Laboratory of Organic Materials Testing Technology & Quality Evaluation, No. 7, Fengxian Central Road, Haidian District, Beijing, China. E-mail: liuwei@beijinglab.com.cn

^bSchool of Materials Science & Engineering, Beijing Institute of Technology, No. 5 South Street, Zhongguancun Haidian District, Beijing, China. E-mail: pangsp@bit.edu.cn; Fax: +86 010-68913038; Tel: +86 010-68913038



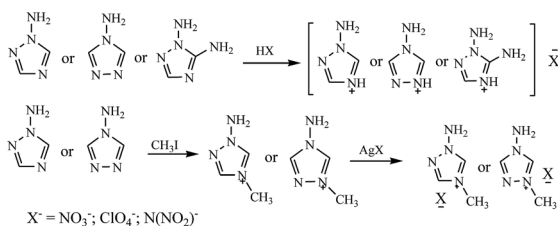
Scheme 5 Energetic salts based on unsubstituted triazolium.

and dinitramide were below 100 °C, which is in the range of ionic liquids.

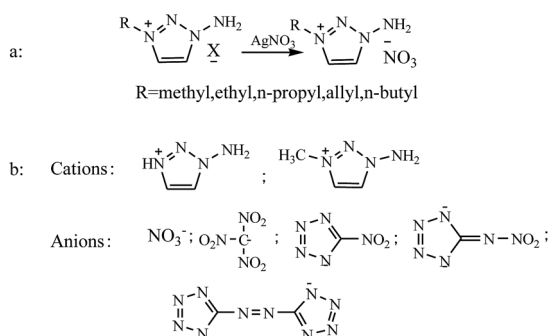
3.2 Amino substituted monocyclic cation-based ionic salts

The incorporation of amino groups into a heterocyclic triazole ring has been proven to be one of the simplest paths to enhancing thermal stability.⁷⁷ Meanwhile, the H atoms in the amino group can form more hydrogen bonds, which can increase the tolerance ability of the compounds towards external impact and friction. Energetic salts based on amino substituted cations have been studied on a large scale, and the involved substrates including triazole, tetrazole, triazine and tetrazine, are discussed in detail in the following section.

3.2.1 Amino-substituted triazolium-based ionic salts. 1-Amino-1,2,4-triazole and 4-amino-1,2,4-triazole can react with nitric acid, perchloric acid and dinitramide directly to form energetic salts.^{78,79} The diamino-substituted compound 1,5-diamino-1,2,4-triazole could also react with nitric acid and perchloric acid directly to form energetic salts (Scheme 6). In addition, 1-amino-1,2,4-triazole and 4-amino-1,2,4-triazole react with iodomethane can lead to the formation of quaternary salts, metathesis of which with various metal salts result in the corresponding energetic salts (Scheme 6).⁷⁹



Scheme 6 Energetic salts based on amino-substituted 1,2,4-triazolium.



Scheme 7 Energetic salts based on amino-substituted 1,2,3-triazolium.

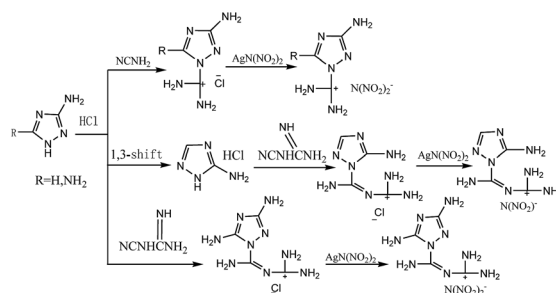
Following the above methods, Drake *et al.*⁸⁰ designed and synthesized a series of nitrate of alkyl-substituted 1-amino-1,2,3-triazolium, involving alkyl groups including methyl, ethyl, *n*-propyl, allyl and *n*-butyl (Scheme 7a). The melting points of all nitrates were below 100 °C, which is in the range of energetic ionic liquids. Based on the existing research, Lin *et al.*⁸¹ systematically produced a series of energetic salts based on 1-amino-1,2,3-triazolium and 1-amino-3-methyl-1,2,3-triazolium (Scheme 7b), and their energetic properties were discussed in detail. For the same anion, energetic salts based on 1-amino-1,2,3-triazolium exhibited higher heats of formation and better detonation properties than the 1-amino-3-methyl-1,2,3-triazolium analogues.

Guanidines were incorporated in 3-amino-1,2,4-triazole and 3,5-diamino-1,2,4-triazole to form a guanidine substituted 3-amino-1,2,4-triazolate cation, which was combined with dinitramide to form energetic salts (Scheme 8).⁷⁹

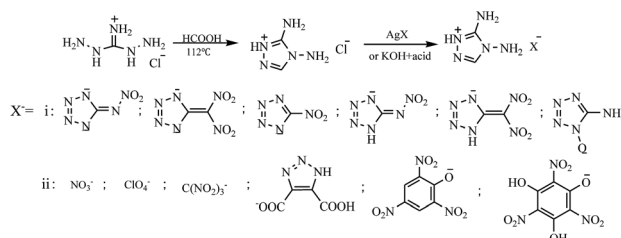
In 2015, Wu *et al.*^{82,83} prepared a series of energetic salts based on 3,4-diamino-1,2,4-triazolium (Scheme 9), and several salts exhibited useful thermal stabilities and low sensitivities towards impact as expected. In addition, most of these salts possess detonation properties comparable to those of TATB, which might be of interest for future applications as insensitive nitrogen-rich energetic materials.

Klapötke¹⁰ processed the obtained 3,4,5-triamino-1,2,4-triazole with iodomethane and combined it with an oxygen-rich anion to form a series of energetic salts (Scheme 10). The salts exhibited excellent thermal stability and low sensitivity, meaning they have potential used as high detonation energetic materials.

3.2.2 Amino-substituted tetrazolium-based ionic salts. Tetrazoles are five-membered heterocycles with four nitrogen

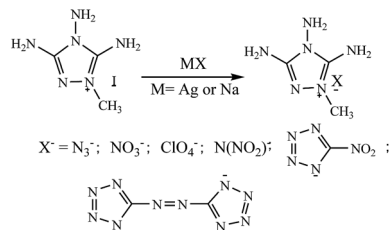


Scheme 8 Energetic salts based on guanidine- and amino-substituted 1,2,4-triazolium.

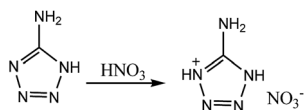


Scheme 9 Energetic salts based on diamino-substituted 1,2,4-triazolium.





Scheme 10 Energetic salts based on poly-amino substituted 1,2,4-triazolium.



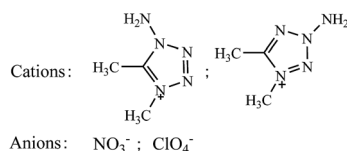
Scheme 11 Energetic salts based on amino substituted tetrazolium.

atoms in the ring. From 1,2,4-triazole ($+109.0 \text{ kJ mol}^{-1}$) to tetrazole ($237.2 \text{ kJ mol}^{-1}$), the heats of formation increase significantly. Energetic salts based on tetrazolium have been less frequently reported, with most studies referring to amino-substituted tetrazolium.

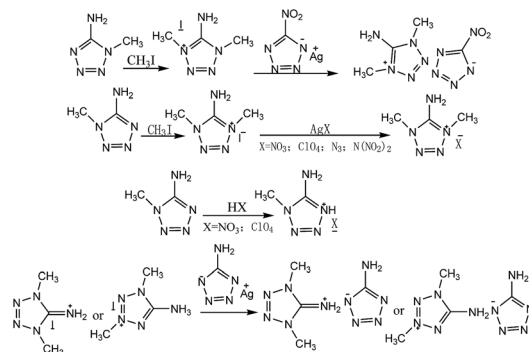
Denffer *et al.*⁸⁴ synthesized a 5-aminotetrazolium nitrate (Scheme 11), whose detonation properties were computed through the Kamlet–Jacobs equation, with a detonation press at 35.7 GPa and a detonation velocity at 8898 m s^{-1} , higher than those of RDX, and close to those of HMX.

Methyl groups can be incorporated in 1-aminotetrazole and 2-aminotetrazole to construct energetic salts. Shreeve *et al.*^{78,85} reported the synthesis of nitrates and perchlorates based on dimethyl-substituted 1-aminotetrazole and 2-aminotetrazole (Scheme 12), which exhibited excellent thermal stabilities and could be applied as components of low signal propellants.

Klapötke *et al.*⁸⁶ processed 1-methyl-5-aminotetrazole with iodomethane to achieve 1,4-dimethyl-5-aminotetrazolium iodate, the metathesis of which with silver 5-nitrotetrazolium to produce 1,4-dimethyl-5-amino-tetrazolium 5-nitrotetrazolate (Scheme 13). The obtained energetic ionic salt exhibited a safe energetic material, but its low detonation velocity, even lower than that of TNT, limited its application. Subsequently, Karaghiosoff *et al.*⁸⁷ reported the synthesis of the nitrate, perchlorate, azide and dinitramide of 1,4-dimethyl-5-aminotetrazolium (Scheme 9), which all exhibited excellent thermal stabilities with decomposition temperatures mostly over 200°C . The impact sensitivities of the nitrate and dinitramide were over 30 J, but the perchlorate was sensitive to impact. Meanwhile,



Scheme 12 Energetic salts based on dimethyl substituted aminotetrazolium.



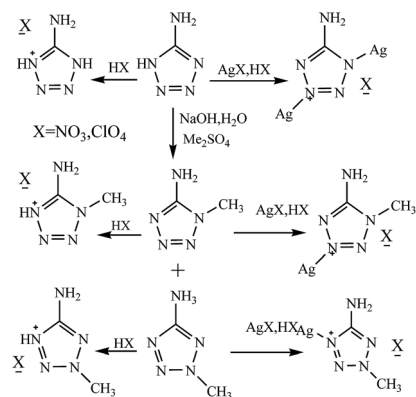
Scheme 13 Energetic salts based on dimethyl-substituted 5-aminotetrazolium.

another nitrate and perchlorate were obtained through the direct acidification of nitric and perchloric acids.

Klapötke *et al.*⁸⁸ reacted 1-methyl-5-aminotetrazole with iodomethane, resulting in the formation of two isomeric cations, which were combined with 5-aminotetrazolium to form the corresponding energetic salts (Scheme 13). Both the obtained energetic salts exhibited decomposition temperature over 200°C and insensitivities towards both impact and friction. Their detonation velocities were at about 8000 m s^{-1} , higher than that of TNT, meaning they could be used as insensitive energetic materials.

In 2009, Klapötke *et al.*⁸⁹ not only reported the synthesis of energetic salts based on 5-aminotetrazolium and 1-methyl-5-aminotetrazolium, but also obtained novel silver substituted 5-aminotetrazolium derivative cations (Scheme 14). The energetic salts based on silver substituted cations were extremely sensitive, but they were more environmental friendly than lead(II) diazide in initiation devices for civil and military applications.

The hydrogen atom of 5-aminotetrazole can be substituted by another amino group to form 1,5-diaminotetrazole, which could undergo acidification or methylation into energetic cations that can be used to construct energetic salts. Klapötke *et al.*⁹⁰ first obtained 1,5-diamino-4-methyltetrazolium iodate through the methylation of 1,5-diaminotetrazole. Subsequently, 1,5-diamino-



Scheme 14 Energetic salts based on silver substituted 5-aminotetrazolium.



4-methyltetrazolium dinitramide was obtained through metathesis (Scheme 15). Later on, Klapötke *et al.*⁹¹ reported a safer path to synthesizing 1,5-diamino-4-methyltetrazolium 5-nitrotetrazolate (Scheme 14), but its detonation property was just comparable to that of TNT. Following the same methods, Ruiz *et al.*⁹² synthesized other energetic salts of 1,5-diamino-4-methyltetrazolium, including a nitrate, a dinitramide and an azide (Scheme 15), whose detonation properties were calculated through the Kamlet–Jacobs equation. The detonation velocities of the nitrate and dinitramide were both comparable to that of RDX, while the nitrate was insensitive to impact (>40 J), but other salts were sensitive to impact. In addition, Ruiz *et al.* obtained the nitrate and perchlorate of 1,5-diaminotetrazolium through the acidification of nitric acid and perchloric acid, respectively. Tao *et al.*⁹³ obtained other oxygen-rich salts of 1,5-diaminotetrazolium through acidification directly, including 5-nitrotetrazolate, 3,5-dinitro-1,2,4-triazolate and 2,4,5-trinitroimidazolate (Scheme 15). These three oxygen-rich salts all exhibited thermal stability with decomposition temperatures over 180 °C.

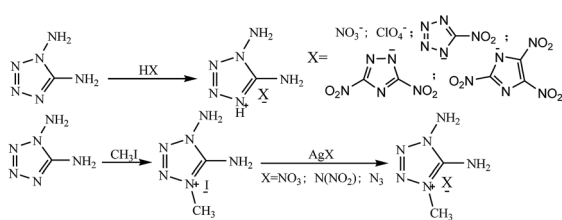
In 2012, Klapötke *et al.*⁹⁴ obtained the first tetrazolium cation containing three amino groups on the same tetrazole ring through the amination of the neutral tetrazole species (1,5-diaminotetrazole) (Scheme 16). The target cation, 1,4,5-triaminotetrazolium, at over 84% nitrogen extends its use in explosive materials as well as propellant formulations. Meanwhile, its energetic salt nitrate and nitrotetrazolate 2-oxide were synthesized and fully characterized. The two salts possessed moderate densities of 1.663 g cm⁻³ and 1.710 g cm⁻³, respectively. Their detonation properties were comparable to those of RDX. Their low thermal stabilities prevent them from being practical energetic materials; however, the study did indicate that there is a limit to the thermal stability as heats of formation and the associated nitrogen content increase.

3.2.3 Amino-substituted triazine cation-based ionic salts. 1,3,5-Triazine possesses a high density, a high heat of formation

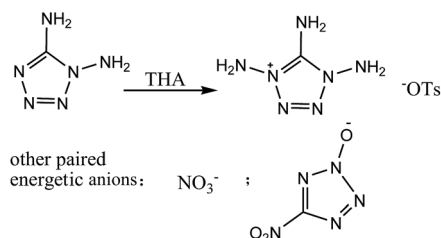
and excellent thermal stability, and is important precursor for the synthesis of energetic materials. 1,3,5-Triazine has three positions for modification, therefore various energetic groups such as amino and nitroamino groups can be incorporated in the triazine ring to construct energetic backbones. The hydrogen atoms of 1,3,5-triazine can all be substituted by amino groups to form 2,4,6-triamino-1,3,5-triazine, which is an excellent backbone for constructing energetic materials. Mostly research on triazine is based on triazine anions. Shreeve *et al.*³⁶ and Srinivas *et al.*⁵⁶ reported two salts based on a 2,4,6-triamino-1,3,5-triazine cation (Scheme 17a). Both showed excellent thermal stabilities with decomposition temperatures at about 300 °C, and were not sensitive towards impact (IS > 40 J). Based on the obtained triazine energetic cation, first discovered in the 1930s, the author reported series of energetic salts based on the first triazine energetic cation (Scheme 17b). The novel oxygen-containing triazine cation was the first oxygen-incorporated heterocyclic cation, which improved the oxygen balance of the energetic cation. Those obtained energetic salts exhibited excellent thermal stabilities and safety, while some of them possessed detonation properties comparable to TATB, meaning they could be potential substitutes for TATB.

3.3 Alkyl-substituted monocyclic cation-based ionic salts

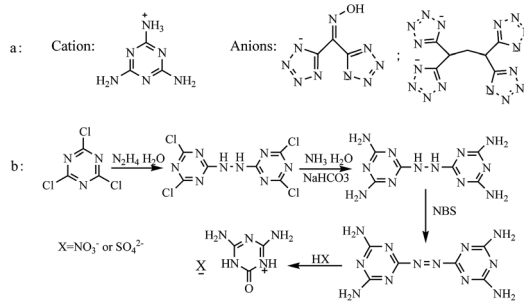
The incorporation of methyl groups into heterocycle compounds can lower the melting points of the compounds, especially for imidazole compounds, which can be used as energetic cations to synthesize energetic ionic liquids. In 2004, Ogiwara *et al.*⁹⁵ combined 1-ethyl-3-methyl-imidazolium with 1,2,4-triazolate and tetrazolate (Scheme 18) separately, to synthesize the corresponding energetic ionic liquids. In 2005, Katritzky *et al.*⁹⁶ combined 1-butyl-3-methyl-imidazolium with



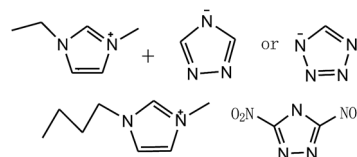
Scheme 15 Energetic salts based on 1,5-diaminotetrazolium and its derivatives.



Scheme 16 Energetic salts based on 1,4,5-triaminotetrazolium.



Scheme 17 Energetic salts based on amino-substituted triazine cations.

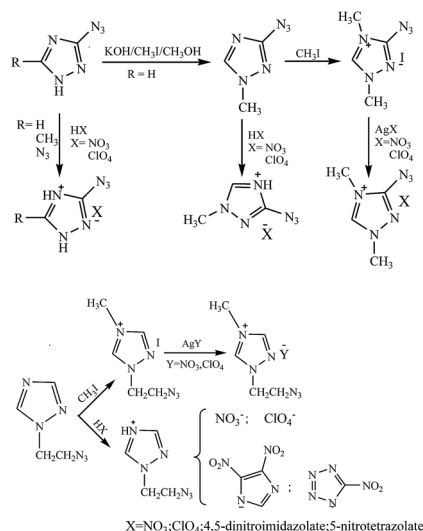


Scheme 18 Energetic salts based on methyl-substituted imidazolium.

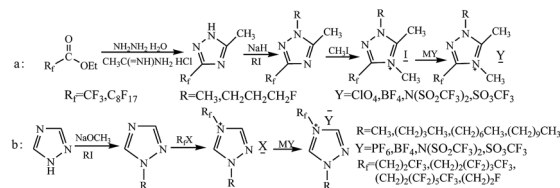


Scheme 19 Energetic salts based on nitro or azide substituted imidazolium.

The processing of a fluoroalkyl-substituted ethyl acetate derivative with hydrazine hydrate produces a fluoroalkyl substituted 1,2,4-triazole, which could be methylated to form fluoroalkyl-substituted 1,2,4-triazolium cation. Following this method, Xue *et al.*⁹⁸ designed and synthesized a series of energetic salts based on a fluoroalkyl-substituted 1,2,4-triazolium cation (Scheme 21a). And if fluorine containing methylation



Scheme 20 Energetic salts based on azido-substituted triazolium.

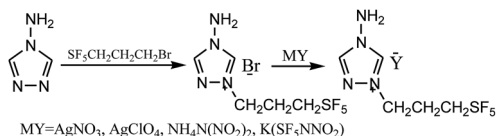


Scheme 21 Energetic salts based on fluoroalkyl-substituted triazolium.

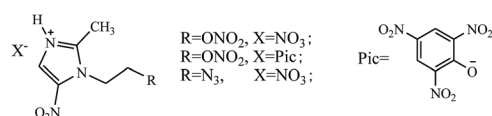
Romero¹⁰¹ reported new energetic ionic liquids derived from metronidazole (Scheme 23). The obtained cation contained some oxygen-rich substituted groups ($-\text{NO}_2$ and $-\text{ONO}_2$), which are useful for improving the oxygen balance of energetic salts. The synthesized energetic salts exhibited good thermal stabilities with decomposition temperatures ranging from 144.0 to 192.8 °C, but their detonation properties were not studied.

3.4 Hydrazine-substituted monocyclic cation-based ionic salts

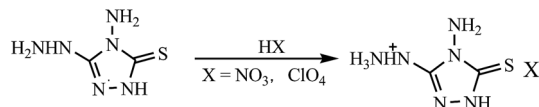
Wu *et al.*¹⁰² processed amino-, hydrazino- and mercapto-substituted 1,2,4-triazole with nitrate acid or perchloric acid



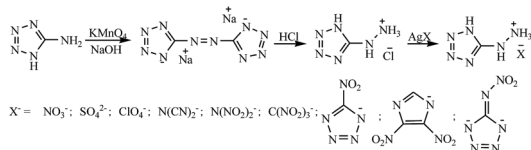
Scheme 22 Energetic salts based on SF₅ containing alkyl-substituted triazolium.



Scheme 23 Energetic salts derived from metronidazole.



Scheme 24 Energetic salts based on hydrazine-substituted triazolium.



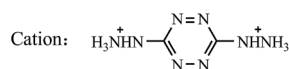
Scheme 25 Energetic salts based on hydrazine-substituted tetrazolium.

directly, and the corresponding energetic salts were obtained (Scheme 24), but their energetic properties were not studied.

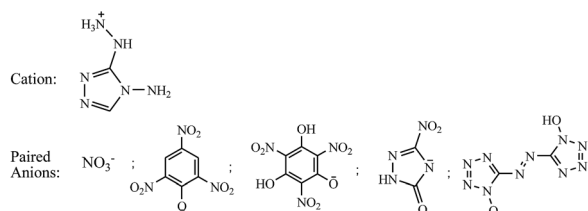
Based on the obtained 5,5'-azobis-tetrazole, we treated it with chlorate acid, and 5-hydrazine tetrazolium chlorate was produced, metathesis of which with various metal salts resulted in a series of energetic salts (Scheme 25).¹⁰³ These salts possess relatively high densities, in which perchlorate reach as high as 2.068 g cm⁻³; meanwhile, these salts exhibited excellent thermal stabilities, with decomposition temperatures all above 150 °C. In addition, their detonation properties are comparable to those of HMX and these salts exhibited moderate impact sensitivities (10 J), meaning they have wide application prospects.

Hydrazine could also be incorporated with tetrazine to form energetic cations, which were paired with the obtained novel anions to produce energetic salts (Scheme 26).^{48,49,55} These salts exhibited relatively high densities (above 1.80 g cm⁻³) and detonation properties comparable to that of RDX.

Recently, Wu *et al.*¹⁰⁴ reported a new series of energetic salts based on 3-hydeazino-4-amino-1,2,4-triazolium (Scheme 27). The obtained salts exhibited relatively high densities ranging from 1.649 to 1.858 g cm⁻³ and excellent thermal stabilities with decomposition temperatures ranging from 168 to 266 °C.



Scheme 26 Energetic cation of hydrazinium-substituted tetrazine.



Scheme 27 Energetic salts based on 3-hydrazino-4-amino-1,2,4-triazolium.

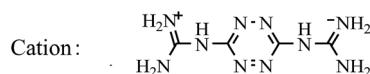
However, most of their detonation properties were lower than those of TATB, which might limit their application.

3.5 Guanidine-substituted monocyclic cations-based ionic salts

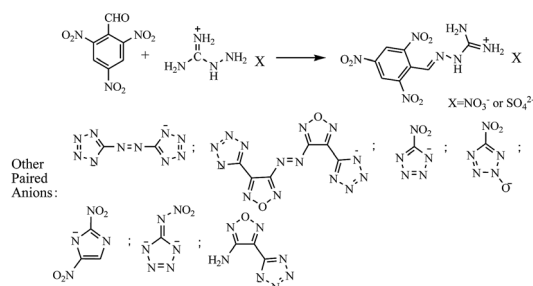
Guanidine is a thermally stable group with high nitrogen content, therefore, the introduction of guanidine groups into tetrazine could improve the nitrogen content and thermal stability. The 3,6-diguanidine-1,2,4,5-tetrazine cation is an excellent energetic ionic ligand, which is widely used in constructing energetic salts (Scheme 28).^{17,21,28,29,46,49,53} Most of these salts show excellent thermal stabilities, but their densities are mostly not very high.

As for the feature of electron-withdrawing inductive effects from the nitro groups, almost all the compounds containing polynitro groups act as anions. Wu *et al.*¹⁰⁵ reported a novel cation containing guanidinium group as well as a picryl moiety, upon which a series of energetic salts were synthesized (Scheme 29). All the energetic salts exhibited excellent thermal stabilities, most over 180 °C, meanwhile, these salts performed sustainable sensitivities towards impact, friction and electrostatic discharge. Moreover, these salts possessed detonation properties comparable to those of TATB, which made them promising candidates for energetic materials.

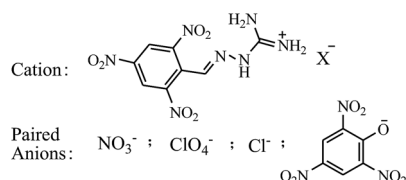
Recently, Klapötke *et al.*¹⁰⁶ created other salts based on guanidinium-substituted polynitroarene (Scheme 30). These salts all exhibited excellent thermal stabilities with decomposition



Scheme 28 Energetic cation of guanidinium-substituted tetrazine.



Scheme 29 Energetic salts based on guanidinium-substituted polynitroarene.



Scheme 30 Other energetic salts based on guanidinium-substituted polynitroarene.



temperatures over 200 °C. But their detonation properties were only comparable to those of TNT, which might limit their potential application.

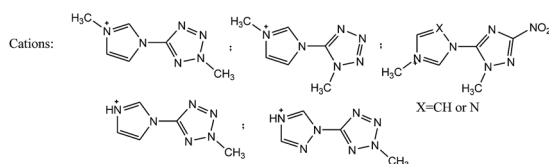
4. Dicyclic and polycyclic cations-based ionic salts

Compared with monocyclic cations, bridged polycyclic cations lay denser and possess higher nitrogen contents, which are useful for improving the energetic performance.

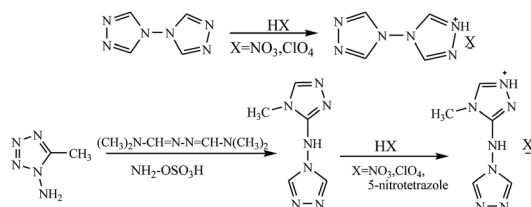
Gao *et al.*¹⁰⁷ obtained C–N bridged imidazole and triazole or tetrazole cations through the processing of methylsulfonyl and nitro-substituted imidazole, which were paired with nitric or perchlorate to produce a series of energetic salts (Scheme 31). The obtained energetic salts exhibited excellent thermal stabilities and moderate densities, but their detonation properties were not studied.

A N–N bridge dicyclic cation has been reported. In 2005, Shreeve *et al.*¹⁰⁸ reported the synthesis of 4,4-bis-1,2,4-triazole, which was processed with nitric acid and perchlorate acid, respectively, and corresponding energetic salts were obtained. Additionally, they reported another dicyclic cation, *N*-4-(1,2,4-triazole)-*N*-3-(4-methyl-1,2,4-triazolium)amine, and obtained its nitrate, perchlorate and 5-nitro-tetrazolate (Scheme 32). For the obtained energetic salts, perchlorate exhibited the best thermal stability and the highest density.

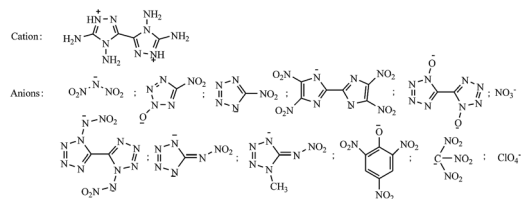
Recently, Klapötke *et al.*¹⁰⁹ designed and synthesized series of poly-nitrogen and oxygen-rich energetic salts 5,5'-bis-(3,4-diamino-1,2,4-triazolium) cation (Scheme 33), which exhibited relatively high densities ranging from 1.65 to 1.87 g cm⁻³. All these energetic salts decomposed over 200 °C except for the nitroformate salt. In addition, these energetic salts showed excellent detonation properties, with detonation velocities ranging from 8051 to 9053 m s⁻¹, detonation pressures ranging from 22.1 to 34.3 kPa. However, the high sensitivities towards impact (<10 J) limited their potential application.



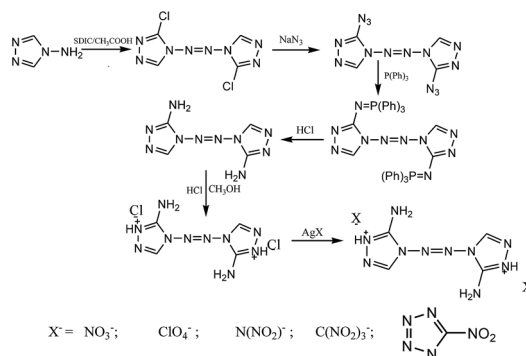
Scheme 31 Energetic salts based on C–N bridged energetic dicyclic cations.



Scheme 32 The N–N bridged energetic cation.



Scheme 33 Energetic salts based on C–C bridged energetic dicyclic cation.



Scheme 34 Energetic salts based on azo-bridged energetic dicyclic cation.

In the previous study, the introduction of azo group has been proven to be an effective path to improving the densities and heats of formation.¹¹⁰ To achieve high performance energetic salts, the author synthesized a series of energetic salts based on the azo group bridged dicyclic cation, 3,3'-diamino-4,4'-azo-1,2,4-triazolium (Scheme 34).¹¹¹ All the obtained energetic salts exhibited high thermal stabilities with decomposition temperatures over 200 °C except for the nitroformate. These energetic salts showed relatively high densities ranging from 1.71 to 1.99 g cm⁻³. Meanwhile, these energetic salts exhibited moderate sensitivities and excellent detonation properties, some even higher than those of HMX, making them potential substitutes for HMX.

5. Conclusions

In the pursuit of high performance energetic salts, large amounts of novel structured energetic anions/cations have been reported. However, energetic cations are reported on a lesser scale, and the reported energetic cations often possess poor oxygen balance, which become the primary limitation to promoting the energetic properties of energetic salts.

From simple linear structures to N-heterocyclic structures, plenty of novel energetic cations have been reported (Fig. 2). Simultaneously, a significant number of high performance energetic salts have been obtained. For the linear cations, they pack denser energetic salts, which usually possess higher densities; however, their simple structures supply less space for modification. As for the monocyclic cations, the N-heterocyclic structure provide higher heats of formation than the linear



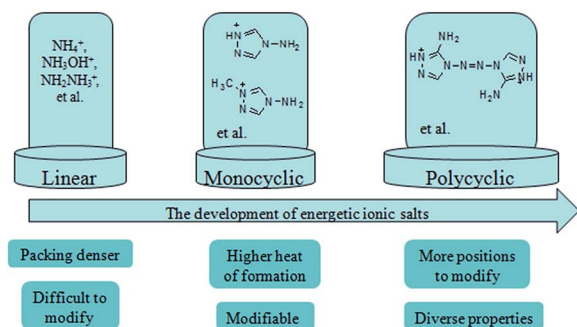


Fig. 2 Development of energetic cations in the research of energetic salts.

structure, while the heterocyclic structure supplies positions for modification, which could improve the energetic properties of energetic salts. Compared with the monocyclic structure, the polycyclic backbones provide more positions to modify, which provide more space for the improvement of energetic performance. With the introduction of various kinds of energetic groups into the polycyclic structures, more and more novel and excellent energetic cations would be obtained in future, which would improve the energetic performance of energetic salts.

Acknowledgements

The authors gratefully acknowledge the support of the National Natural Science Foundation of China (21576026) and the opening project of Beijing Academy of Science and Technology Specific Financial Funds (No. PXM2016_178305_000010).

Notes and references

- V. Thottampudi, P. Yin, J. H. Zhang, D. A. Parrish and J. M. Shreeve, *Chem.-Eur. J.*, 2014, **20**, 542.
- A. A. Dippold and T. M. Klapötke, *J. Am. Chem. Soc.*, 2013, **135**, 9931.
- T. M. Klapötke, N. Mayr, J. Stierstorfer and M. Weyrauther, *Chem.-Eur. J.*, 2014, **20**, 1410.
- N. Kommu, V. D. Ghule, A. S. Kumar and A. K. Sahoo, *Chem.-Asian J.*, 2014, **9**, 166.
- Z. Q. Wang, D. Jishkariani, B. J. Killian, I. Ghiviriga, C. D. Hall, P. J. Steel and A. R. Katritzky, *J. Energ. Mater.*, 2014, **32**, 227.
- Q. H. Zhang, C. L. He, P. Yin and J. M. Shreeve, *Chem.-Asian J.*, 2014, **9**, 212.
- D. E. Chavez, S. K. Hanson, J. M. Veauthier and D. A. Parrish, *Angew. Chem., Int. Ed.*, 2013, **52**, 6876.
- Q. Wu, W. H. Zhu and H. M. Xiao, *J. Mater. Chem. A*, 2014, **2**, 13006.
- R. P. Singh, R. D. Verma, D. T. Meshri and J. M. Shreeve, *Angew. Chem., Int. Ed.*, 2006, **45**, 3584.
- C. Darwich, T. M. Klapötke and C. M. Sabaté, *Chem.-Eur. J.*, 2008, **14**, 5756.
- R. H. Wang, H. Y. Xu, Y. Guo, R. J. Sa and J. M. Shreeve, *J. Am. Chem. Soc.*, 2010, **132**, 11904.
- V. Thottampudi and J. M. Shreeve, *J. Am. Chem. Soc.*, 2011, **133**, 19982.
- T. Fendt, N. Fisher, T. M. Klapötke and J. Stierstorfer, *Inorg. Chem.*, 2011, **50**, 1447.
- R. P. Singh, R. D. Verma, D. T. Meshri and J. M. Shreeve, *Angew. Chem., Int. Ed.*, 2006, **45**, 3584.
- H. X. Gao and J. M. Shreeve, *Chem. Rev.*, 2011, **111**, 7377.
- Q. H. Zhang and J. M. Shreeve, *Chem. Rev.*, 2014, **114**, 10527.
- Y. Q. Zhang, Y. Guo, Y. H. Joo, D. A. Parrish and J. M. Shreeve, *Chem.-Eur. J.*, 2010, **16**, 10778.
- Y. Q. Zhang, Y. G. Huang, D. A. Parrish and J. M. Shreeve, *J. Mater. Chem.*, 2011, **21**, 6891.
- Y. Q. Zhang, D. A. Parrish and J. M. Shreeve, *Chem.-Eur. J.*, 2012, **18**, 9987.
- M. J. Crawford, K. Karaghiosoff, T. M. Klapötke and F. A. Martin, *Inorg. Chem.*, 2009, **48**, 1731.
- V. Thottampudi and J. M. Shreeve, *J. Am. Chem. Soc.*, 2011, **133**, 19982.
- T. M. Klapötke, M. Stein and J. Stierstorfer, *Z. Anorg. Allg. Chem.*, 2008, **634**, 1711.
- T. M. Klapötke, P. Mayer, C. M. Sabaté, J. M. Selch and N. Wiegand, *Inorg. Chem.*, 2008, **47**, 6014.
- M. Göbel, K. Karaghiosoff, T. M. Klapötke, D. G. Piercy and J. Stierstorfer, *J. Am. Chem. Soc.*, 2010, **132**, 17216.
- T. M. Klapötke and J. Stierstorfer, *J. Am. Chem. Soc.*, 2009, **131**, 1122.
- T. M. Klapötke, D. G. Piercy and J. Stierstorfer, *Chem.-Eur. J.*, 2011, **17**, 13068.
- R. Haiges and K. O. Christe, *Inorg. Chem.*, 2013, **52**, 7249.
- H. X. Gao, R. H. Wang, B. Twamley, M. A. Hiskey and J. M. Shreeve, *Chem. Commun.*, 2006, 4007.
- R. H. Wang, H. Y. Xu, Y. Guo, R. J. Sa and J. M. Shreeve, *J. Am. Chem. Soc.*, 2010, **132**, 11904.
- A. A. Dippold, T. M. Klapötke and N. Winter, *Eur. J. Inorg. Chem.*, 2012, **2012**, 3474.
- A. A. Dippold and T. M. Klapötke, *J. Am. Chem. Soc.*, 2013, **135**, 9931.
- N. Fischer, D. Izsák, T. M. Klapötke, S. Rappenglück and J. Stierstorfer, *Chem.-Eur. J.*, 2012, **18**, 4051.
- N. Fischer, L. Gao, T. M. Klapötke and J. Stierstorfer, *Polyhedron*, 2013, **51**, 201.
- D. Izsák, T. M. Klapötke and S. Reuter, *Eur. J. Inorg. Chem.*, 2013, **2013**, 5641.
- S. Huber, D. Izsák, K. Karaghiosoff and S. Reuter, *Propellants, Explos., Pyrotech.*, 2014, **39**, 793.
- D. Chand, D. A. Parrish and J. M. Shreeve, *J. Mater. Chem. A*, 2013, **1**, 15383.
- R. H. Wang, Y. Guo, Z. Zeng, B. Twamley and J. M. Shreeve, *Chem.-Eur. J.*, 2009, **15**, 2625.
- L. X. Liang, K. Wang, C. M. Bian, L. M. Ling and Z. M. Zhou, *Chem.-Eur. J.*, 2013, **19**, 14902.
- T. M. Klapötke, C. M. Sabaté and M. Rasp, *J. Mater. Chem.*, 2009, **19**, 2240.
- Y. Guo, H. X. Gao, B. Twamley and J. M. Shreeve, *Adv. Mater.*, 2007, **19**, 2884.
- M. Eberspächer, T. M. Klapötke and C. M. Sabaté, *Helv. Chim. Acta*, 2009, **92**, 977.



- 42 Y. H. Joo and J. M. Shreeve, *Angew. Chem., Int. Ed.*, 2010, **49**, 7320.
- 43 T. M. Klapötke, N. Mayr, J. Stierstorfer and M. Weyrauther, *Chem.–Eur. J.*, 2014, **20**, 1410.
- 44 J. H. Zhang and J. M. Shreeve, *J. Am. Chem. Soc.*, 2014, **136**, 4437.
- 45 Y. G. Huang, H. X. Gao, B. Twamley and J. M. Shreeve, *Eur. J. Inorg. Chem.*, 2008, **2008**, 2560.
- 46 T. Fendt, N. Fischer, T. M. Klapötke and J. Stierstorfer, *Inorg. Chem.*, 2011, **50**, 1447.
- 47 A. Hammerl, T. M. Klapötke, H. Nöth and M. Warchhold, *Inorg. Chem.*, 2001, **40**, 3570.
- 48 Y. H. Joo and J. M. Shreeve, *Chem.–Eur. J.*, 2009, **15**, 3198.
- 49 H. X. Gao, C. F. Ye, O. D. Gupta, J. C. Xiao, M. A. Hiskey, B. Twamley and J. M. Shreeve, *Chem.–Eur. J.*, 2007, **13**, 3853.
- 50 H. X. Gao, Y. G. Huang, C. F. Ye and B. Twamley, *Chem.–Eur. J.*, 2008, **14**, 5596.
- 51 T. M. Klapötke, J. Stierstorfer and A. Wallek, *Chem. Mater.*, 2008, **20**, 4519.
- 52 R. H. Wang, Y. Guo, Z. Zeng and J. M. Shreeve, *Chem. Commun.*, 2009, 2697.
- 53 Y. G. Huang, Y. Q. Zhang and J. M. Shreeve, *Chem. Eur. J.*, 2011, **17**, 1538.
- 54 A. Hammerl, M. A. Hiskey, G. Holl, T. M. Klapötke, K. Polborn, J. Stierstorfer and J. M. Shreeve, *Chem. Mater.*, 2005, **17**, 3784.
- 55 Y. H. Joo and J. M. Shreeve, *J. Am. Chem. Soc.*, 2010, **132**, 15081.
- 56 D. Srinivas, V. D. Ghule, K. Muralidharan and H. D. B. Jenkins, *Chem.–Asian J.*, 2013, **8**, 1023.
- 57 Y. Tang, H. Gao, L. A. Mitchell, D. A. Parrish and J. M. Shreeve, *Angew. Chem., Int. Ed.*, 2016, **55**, 3200.
- 58 J. H. Zhang, S. Dharavath, L. A. Mitchell, D. A. Parrish and J. M. Shreeve, *J. Am. Chem. Soc.*, 2016, **138**, 7500.
- 59 Y. T. Gao, L. M. Zhao, F. Q. Pang, X. J. Qi, J. L. Huang and F. X. Chen, *Chin. Chem. Lett.*, 2016, **27**, 433.
- 60 P. Yin, C. L. He and J. M. Shreeve, *J. Mater. Chem. A*, 2016, **4**, 1514.
- 61 P. Yin, C. L. He and J. M. Shreeve, *Chem.–Eur. J.*, 2016, **22**, 2108.
- 62 H. F. Huang, Y. M. Shi, Y. F. Liu and J. Yang, *Chem.–Asian J.*, 2016, **11**, 1688.
- 63 H. F. Huang, Y. M. Shi, Y. Li, Y. F. Liu and J. Yang, *RSC Adv.*, 2016, **6**, 64568.
- 64 Y. Li, H. Huang, X. Lin, R. Pan and J. Zhang, *RSC Adv.*, 2016, **6**, 54310.
- 65 Y. Tang, C. He, L. A. Mitchell, D. A. Parrish and J. M. Shreeve, *Chem.–Eur. J.*, 2016, **22**, 11846.
- 66 Q. Wang, H. J. Lu, F. Q. Pang, J. L. Huang, F. D. Nie and F. X. Chen, *RSC Adv.*, 2016, **6**, 56827.
- 67 Z. B. Zhang, L. Yin, X. Yin and J. G. Zhang, *Crystals*, 2016, **6**, 21.
- 68 C. L. He, Y. X. Tang, L. A. Mitchell, D. A. Parrish and J. M. Shreeve, *J. Mater. Chem. A*, 2016, **4**, 8969.
- 69 Q. Q. Liu, B. Jin, R. F. Peng, Z. C. Guo, J. Zhao, Q. C. Zhang and Y. Shang, *J. Mater. Chem. A*, 2016, **4**, 4971.
- 70 T. M. Klapötke, J. Stierstorfer, M. Weyrauther and T. G. Witkowski, *Chem.–Eur. J.*, 2016, **22**, 8619.
- 71 J. P. Zhu, S. H. Jin, L. Wan, C. Y. Zhang, L. J. Li, S. S. Chen and Q. H. Shu, *Dalton Trans.*, 2016, **45**, 3590.
- 72 T. M. Klapötke, C. Pflüger and M. W. Reintinger, *Eur. J. Inorg. Chem.*, 2016, **2016**, 138.
- 73 D. Izsk, T. M. Klapötke, F. H. Lutter and C. Pflüger, *Ber. Dtsch. Chem. Ges.*, 2016, **2016**, 1720.
- 74 V. Forquet, C. M. Sabate, G. Jacob, Y. Guelou, H. Delalu and C. Darwich, *Chem.–Asian J.*, 2015, **10**, 1668.
- 75 T. Fei, H. W. Cai, Y. Q. Zhang, L. Liu and S. J. Zhang, *J. Energ. Mater.*, 2016, **34**, 138.
- 76 G. Drake, T. Hawkins, A. Brand, L. Hall, M. McKay, A. Vij and I. Ismail, *Propellants, Explos., Pyrotech.*, 2003, **28**, 174.
- 77 J. Aprawal, *Prog. Energy Combust. Sci.*, 1998, **24**, 1.
- 78 H. Xue, S. W. Arritt, B. Twamley and J. M. Shreeve, *Inorg. Chem.*, 2004, **43**, 7972.
- 79 Z. Zeng, R. H. Wang, B. Twamley, D. A. Parrish and J. M. Shreeve, *Chem. Mater.*, 2008, **20**, 6176.
- 80 G. Drake, G. Kaplan, L. Hall, T. Hawkins and J. Larue, *J. Chem. Crystallogr.*, 2007, **37**, 15.
- 81 Q. H. Lin, Y. C. Li, Y. Y. Li, Z. Wang, W. Liu, C. Qi and S. P. Pang, *J. Mater. Chem.*, 2012, **22**, 666.
- 82 J. T. Wu, J. G. Zhang, X. Yin, Z. Y. Cheng and C. X. Xu, *New J. Chem.*, 2015, **39**, 5265.
- 83 J. T. Wu, J. G. Zhang, X. Yin and K. Wu, *Chem.–Asian J.*, 2015, **10**, 1239–1244.
- 84 M. V. Denffer, T. M. Klapötke, G. Kramer, G. Spieß, J. M. Welch and G. Heeb, *Propellants, Explos., Pyrotech.*, 2005, **30**, 191.
- 85 H. Xue, Y. Gao, B. Twamley and J. M. Shreeve, *Chem. Mater.*, 2005, **17**, 191.
- 86 T. M. Klapötke, K. Karaghiosoff, P. Mayer, A. Penger and J. M. Welch, *Propellants, Explos., Pyrotech.*, 2006, **31**, 188.
- 87 K. Karaghiosoff, T. M. Klapötke, P. Mayer, C. M. Sabsté, A. Penger and J. M. Welch, *Inorg. Chem.*, 2008, **47**, 1007.
- 88 T. M. Klapötke and C. M. Sabaté, *Z. Anorg. Allg. Chem.*, 2009, **635**, 1812.
- 89 K. Karaghiosoff, T. M. Klapötke and C. M. Sabaté, *Chem.–Eur. J.*, 2009, **15**, 1164.
- 90 T. M. Klapötke, P. Mayer, A. Schulz and J. J. Weigand, *J. Am. Chem. Soc.*, 2005, **127**, 2032.
- 91 T. M. Klapötke, C. M. Sabaté and J. M. Welch, *Z. Anorg. Allg. Chem.*, 2008, **634**, 857.
- 92 J. C. G. Ruiz, G. Holl, K. Karaghiosoff, T. M. Klapötke, K. Löhnwitz, P. Mayer, H. Nöth, K. Polborn, C. J. Rohbogner, M. Suter and J. J. Weigand, *Inorg. Chem.*, 2005, **44**, 4237.
- 93 G. H. Tao, Y. Guo, D. A. Parrish and J. M. Shreeve, *J. Mater. Chem.*, 2010, **20**, 2999.
- 94 T. M. Klapötke, D. G. Piercey and J. Stierstorfer, *Eur. J. Inorg. Chem.*, 2012, **2012**, 5694.
- 95 W. Ogiwara, M. Yoshizawa and H. Ohno, *Chem. Lett.*, 2004, **33**, 1022.
- 96 A. R. Katrizky, S. Singh, K. Kostyantyn, J. D. Holbrey, M. Smiglak, W. M. Reichert and R. D. Rogers, *Chem. Commun.*, 2005, 868.
- 97 H. Xue and J. M. Shreeve, *Adv. Mater.*, 2005, **17**, 2142.



- 98 H. Xue, B. Twamley and J. M. Shreeve, *J. Org. Chem.*, 2004, **69**, 1397.
- 99 Y. R. Mirazei, B. Twamley and J. M. Shreeve, *J. Org. Chem.*, 2002, **67**, 9340.
- 100 H. X. Gao, C. F. Ye, R. W. Winter, G. L. Gard, M. E. Sitzmann and J. M. Shreeve, *Eur. J. Inorg. Chem.*, 2006, **2006**, 3221.
- 101 M. A. Romero, *Org. Chem. Int.*, 2016, **2016**, 4705809.
- 102 J. T. Wu, J. G. Zhang, X. Yin and T. L. Zhang, *Z. Anorg. Allg. Chem.*, 2014, **640**, 2544.
- 103 Q. H. Lin, Y. C. Li, C. Qi, W. Liu, Y. Wang and S. P. Pang, *J. Mater. Chem. A*, 2013, **1**, 6776.
- 104 J. T. Wu, J. G. Zhang, X. Yin and L. Wu, *New J. Chem.*, 2016, **40**, 5414.
- 105 B. Wu, Z. X. Wang, H. W. Yang, Q. H. Lin, X. H. Ju, C. X. Lu and G. B. Cheng, *New J. Chem.*, 2015, **39**, 893.
- 106 T. M. Klapötke, F. Mieskes, J. Stierstorfer and M. Weyrauther, *Propellants, Explos., Pyrotech.*, 2016, **41**, 217.
- 107 Y. Gao, C. F. Ye, B. Twamley and J. M. Shreeve, *Chem.–Eur. J.*, 2006, **12**, 9010.
- 108 H. Xue, B. Twamley and J. M. Shreeve, *Inorg. Chem.*, 2005, **44**, 7009.
- 109 T. M. Klapötke, P. C. Schmid, S. Schnell and J. Stierstorfer, *J. Mater. Chem. A*, 2015, **3**, 2658.
- 110 C. Qi, S. H. Li, Y. C. Li, Y. Wang, X. K. Chen and S. P. Pang, *J. Mater. Chem.*, 2011, **21**, 3221.
- 111 W. Liu, S. H. Li, Y. C. Li, Y. Z. Yang, Y. Yu and S. P. Pang, *J. Mater. Chem. A*, 2014, **2**, 15978.

