Introduction

Since the first deployment of chemical warfare agents (CWAs) during the First World War, research into efficient decontamination routes has become necessary for immediate applications, and also for the destruction of CWA stockpiles as set out in the 1992 Chemical Weapons Convention Treaty (demilitarisation). Whilst a variety of fast and effective decontamination routes have been identified, these generally contain a mixture of flammable solvents and corrosive reagents and can be impractical for transportation or decontamination of expensive equipment. For example, DS2 is a combination of nucleophilic diethylenetriamine/ethylene glycol/monomethyl ether/sodium hydroxide mixtures and whilst it is a broadband decontaminant it is highly corrosive towards many materials. Alternate decontamination solutions containing basic hypochlorite (bleach)-based microemulsions are very effective for sulfur mustard decontamination however these are also deemed too corrosive and environmentally unacceptable for widespread use. Therefore new reagents that have a low environmental impact and can be used in different situations on different classes of warfare agents are desirable.

Sulfur mustard (HD), bis-2-chloroethyl sulfide, is a potent vesicant with a long environmental persistence that makes decontamination challenging. Generally destruction of HD can occur via three different pathways (Scheme 1). Currently known dehydrohalogenation procedures can be problematic due to the reversible addition of HCl and considered too slow in comparison to the other decontamination pathways whilst at ambient temperatures hydrolysis is limited by the low aqueous solubility of HD. Oxidation is currently one of the most effective pathways of decontamination; however care must be taken to form the monooxidation product, as the sulfone is a potent vesicant in its own right.

The other major class, nerve agents, are organophosphate compounds that were originally developed as pesticides until their highly toxic nature was recognised. Nerve agents can be divided into two main classes: non-persistent G- (e.g. Sarin) and persistent V- (e.g. VX) series, where the persistence relates to the relative ease of degradation or propensity to remain in the environment.

Traditional routes for decontamination of VX have centred around its susceptibility towards nucleophilic attack, but again the control of product formation is imperative. In the simplest case addition of H2O yields several products, but the formation of EA-2192 is of concern as it is nearly as toxic as VX and is less reactive towards further nucleophilic attack (Scheme 2). N-Heterocyclic carbenes (NHCs) have transformed modern organometallic chemistry. The strongly Lewis basic σ-donor ligands have been shown to bind to many metals leading to...
widespread applications, notably their use in homogeneous catalysis with late transition metals for alkene metathesis and C–C coupling reactions. In relation to decontamination and demilitarisation of CW agents, the range of reactivity available to NHCs and their highly tuneable nature makes them attractive candidates for these processes due to their ability to act as strong nucleophiles in organocatalysis, as well as organic bases. Oxidative CWA destruction pathways can also be considered in combination with right choice of metal centre. Many coinage metal NHC complexes made for medicinal applications display very high water stability, while homogeneous catalysts based on Pd and V show both a high stability towards oxidation and great efficacy as oxidation catalysts, and in particular vanadium doped silica has been previously shown to be effective for the oxidation of CEES. The redox couple of VO$_2^+$/VO$^{2+}$ (vanadyl) complexes is +1.00 V, and it has been demonstrated that the complex VOCl$_3$(IMes) is air-stable.

We have been studying the cooperative reactivity of metal–NHC complexes in which the metal–C bond is relatively labile, and can give rise to reactions of both the metal and NHC. We have previously shown a range of carbon–element bond formation and cleavage reactions.

Herein we report the effectiveness of a range of air and moisture stable metal NHC complexes for the stoichiometric and catalytic destruction of both H- (mustards) and V- (nerve) type chemical warfare agent (CWA) simulants shown in Fig. 1. The use of simulants is required due to strictly controlled production, acquisition, retention or use of warfare agents under Schedule 1 of the Chemical Weapons Convention (CWC). Previous research has shown 2-chloroethyl ethyl sulphide (CEES, referred to as half mustard) is an effective simulant for HD, whilst paraoxon-ethyl and profenofos are used to simulate VX as these contain the desirable P–O and P–S bond vages, respectively. Whilst these simulants are less toxic than the actual CWAs, they are still considered to be very toxic (paraoxon-ethyl: LD50 in Rat = 0.716 mg kg$^{-1}$) and must be handled with great care. Reactions are carried out on a small scale with no more than 5 µL of the chosen CWA simulant, to manage the risks associated with these compounds.

### Results and discussion

#### Candidate metal–NHC complexes

Copper and silver NHC complexes were initially targeted due to their high water-stability and ability to undergo redox reactions, thus providing a good baseline for how metal–NHC complexes may react with CWA simulants. This focused on the use of previously reported, commercially available unsaturated NHCs (denoted IR, and derived from the imidazolium chloride salts IPr·HCl, IMes·HCl and ICy·HCl) and saturated NHCs (denoted SIR, and derived from the imidazolium salts SIPr·HCl, and SIMes·HCl) and a bidentate aryloxide-functionalised imidazolium salt (HOArIPr·HCl), Fig. 2. The silver NHC complexes AgCl(IR) (R = Dipp, Mes, Cy, 3-Ag), AgCl(SIR) (R = Dipp, 4-Ag, Mes, 5-Ag) and corresponding copper NHC complexes CuCl(IR) (R = Dipp, Mes, Cy, Cu), CuCl(SIR) (R = Dipp, Cu, Mes, 5-Cu) are readily obtained from reactions with the corresponding metal oxide. Due to the potential for oxidation destruction pathways the use of the highly oxidising but remarkably air-stable vanadyl NHC complexes VOCl$_3$(IR) (R = Dipp, Mes, Cy) Fig. 2, (1–3)-V were isolated from the stoichiometric addition of VOCl$_3$ to the free carbene. It is of note that whilst the saturated analogues of the vanadium NHC complexes were also isolated they were found to be unstable towards moisture, and therefore were not used in this study (see ESI†).

In addition, metal complexes of the bidentate aryloxide NHC were also made; 6-Ag was made from silver(i)oxide, and the sodium (6-Na) and potassium (6-K) complexes were made from the corresponding MOBu (M = Na or K) salt in situ prior to use.

Reactions of each compound shown in Fig. 2 with each of the three CWA simulants were monitored by $^1$H NMR spectroscopy. Reactions used stoichiometric, excess, or catalytic amounts of the complexes and were accelerated by either heat or photolysis.
Destruction by group 11 metal–NHC complexes

Stoichiometric simulant degradation reactions were followed in 0.5 mL of CDCl₃. Reactions were monitored at intervals by a combination of NMR spectroscopy (¹H and ³¹P where relevant), UV-Vis spectroscopy and GC mass spectrometry. As shown in Scheme 3, complexes (1–5)-Ag showed no reactivity at room temperature or after prolonged heating at 80 °C with any of the simulants. However, upon exposure to low-intensity UV light (254 nm, 6 W) the reactions with CEES showed the conversion of CEES into new compounds after 1 h, according to ¹H NMR spectroscopic analysis. No reaction of the V agent simulants was observed even after prolonged exposure to either 254 nm or 364 nm UV radiation. Full destruction of CEES was observed after 5 h when using an excess of 1-Ag (5 eq.). The ¹H NMR spectra show several new species in solution. Through a combination of HSQC, HMBC, COSY and DOSY 2D NMR spectroscopy experiments the major product was identified as the mono-oxidation product, CEES-O (Scheme 3). The two other major products are attributed to the dehydrohalogenation of CEES and include ethyl(vinyl)sulfide (EVS) and 1,4-thioxane (1,4-TO) which results from the dehydrohalogenation of partially hydrolysed CEES. An approximate product distribution was 80% CEES-O: 8% EVS: 10% 1,4-TO, with several minor products accounting for the remaining 2%.

The fate of complex 1-Ag was also determined by NMR spectroscopy and ICP-OES spectrometry as the imidazolium chloride salt IPr·HCl, and a silver- and sulfur-containing material which was observed to precipitate during the reaction. The scale of these reactions (demanded for safety reasons) make unambiguous analysis difficult, but it is most likely to be silver sulfate.

Kinetic analyses of the reactions of (1–5)-Ag with CEES were carried out to examine the influence of the sterics and electronics of the NHC on the reaction. Reactions between (1–5)-Ag and CEES in CDCl₃ in a quartz tube were monitored by ¹H NMR spectroscopy with mesitylene as an internal standard. NMR spectra were recorded for each sample after 30 minutes periods of UV (254 nm) radiation. The data fitted to a first-order dependence on CEES (Fig. 3), show that 1-Ag is the fastest of all the silver NHC complexes (Fig. S6–10†).

It is proposed that the photolysis cleaves the silver–NHC bond, thus releasing the silver ion, a potent oxidant for CEES, and the free carbene which is active for the dehydrohalogenation of CEES, giving two routes for the destruction of the CWA simulant, Scheme 4a. Reactions of equimolar amounts of Ag₂O and AgCl and CEES were also carried out as control reactions, however they were insoluble in the reaction medium and no decomposition was observed at 80 °C or under photolysis. It is suggested that the NHC plays an important role by both helping solubilise the metal cation whilst also acting as a reagent in its own right.

This hypothesis is backed up by the products formed from the reaction of the free base NHC (Scheme 4b). The equimolar reaction between IPr and CEES at room temperature shows 10% conversion to EVS, the dehydrohalogenation product, within 5 minutes. However, storage for a further hour at room temperature or at 80 °C for 24 h showed no further destruction of CEES, presumably because the remaining NHC decomposed during prolonged contact with air and moisture. A trial reac-
tion using artificial sunlight from a commercially available SAD lamp provided ca. 40% decomposition of CEES within the same 5 h time frame.

The analysis of observed rates gives a reactivity in decreasing order for the NHC of IPr > ICy > IMes > SIPr > SIMes. Saturated NHCs (SIR) are better σ-donors than the unsaturated (IR) analogues. Thus although the free (SIR) carbene could be considered more reactive for the dehydrohalogenation reaction, the efficacy of complexes (1–5)-Ag appears to be dominated by the reaction that cleaves the Ag–NHC bond.

To further confirm this cooperative effect reactions between the metal and the NHC reactions were carried out using the analogous copper NHC complexes. Following the same protocol for the silver complexes, the Cu(i) analogues (1–5)-Cu were combined with 1 equivalent of CEES in the presence of UV light (254 nm). After 1 h the 1H NMR spectra confirm that the Cu–NHC bonds have been broken, showing broad, paramagnetically-shifted resonances which are attributed to the formation of Cu(i) ions arising from aerobic oxidation after release into solution. GC-MS data indicate that no degradation of CEES has occurred in any of the reactions studied. Prolonged exposure of the reactions to UV light show only background reactivity, ca. 10% decomposition of CEES. Since the Cu(i)/Ag0 redox couple is significantly less oxidising than the Ag1+/Ag0 couple (+0.52 V vs. +0.80 V), these observations suggest that both the oxidising metal and the basic NHC are responsible for the CEES destruction. We note that the degradation products arise from both oxidation and dehydrohalogenation, suggesting that the metal cation also plays a role in facilitating dehydrohalogenation. Presumably coordinating of the sulfur to the silver cation renders the CEES active towards attack by the liberated NHC.

**Destruction by vanadium NHC complexes**

Complexes (1–3)-V produce efficient stoichiometric destruction of CEES in 5 hours under UV light (254 nm), Scheme 5a. The reactions appear to involve reduction by the vanadium centre as the 1H NMR spectra of the reaction mixtures show contact-shifted resonances due to the paramagnetic vanadium centre, and must be separated from vanadium-containing materials for identification. Reactions monitored by GC-MS also show the conversion of CEES to new products (Scheme 5a). The major decomposition product is CEES-O (60%), with 2-chloroethyltrisulfide (CEESS) a minor product. Two features are notable: there is no evidence of dehydrohalogenation, and hexachloroethane (PCA) is also formed during the reaction.

The observation of PCA production is notable since it is usually observed to form in samples of CEES that have been stored for long periods of time (tens of years to the best of our knowledge), although there are only a few literature reports of the chlorination of CEES. In these cases the di, tri, and tetrachlorinated sulfides are reported to form, along with hexachloroethane which results from the reaction with excess chlorine radicals. Here however, repetition of the reactions between 2-V and CEES in C6D6 confirm the PCA derives from solvent decomposition, as after 3 h, the new decomposition product diethyl disulfide (CEESS) is formed (Scheme 5b). VOC₃ has been recently shown to effect the oxochlorination of cyclohexane, but if anything, is only a minor contributor here (see ESIF for proposed mechanism).

The complexes (1–3)-V also react with the two V-agent simulants shown in Fig. 1. Scheme 5c shows the reaction of (1–3)-V with both paraxoxon-ethyl and profenofos yield substituted phenol products arising from P-OAr bond cleavage and subsequent hydrolysis through trace moisture in the reaction mixture. These were identified by GC-MS trace after 3 h of exposure to UV light (254 nm) (Scheme 5c), with complete decomposition of both V agent simulants observed after 24 h.

**Destruction by complexes of tethered-NHCs**

To test the hypothesis that a combination of metal and NHC afford enhanced dehydrohalogenation of the H-agent, three different metal complexes of a hemilabile, bidentate aryl oxy-NHC, 6-Ag, 6-Na and 6-K shown in Fig. 2, were made and tested (see ESIF for details).

No reaction between stoichiometric quantities of 6-Ag and CEES was observed at room temperature by 1H NMR spectroscopy, but after 1 h at 80 °C, 25% conversion to the product dehydrohalogenation, EVS, was observed. This was characterised by the characteristic alkene hydrogens of the product (Scheme 6a). The complete conversion of CEES to EVS can be achieved using a catalytic amount of 6-Ag, if additional Ag₂O is added within 5 h, thus rendering the system catalytic in NHC.
The proposed mechanism for this reaction is outlined in Scheme 7, showing how the combination of the silver centre and the NHC can be effective for the destruction of CEES.

Furthermore, similar reactivity can be obtained with the alkali metal NHC complexes 6-Na and 6-K, which give 30% and 15% destruction of CEES in 1 h, respectively (at 80 °C). Again, the selective formation of EVS was identified by $^1$H NMR spectroscopy. The kinetic data (Fig. S27) suggest a small induction period (possibly due to complex formation) and first order dependence on base. It is possible to double the rate of destruction, use of the Fe(III) complex results in oxidative destruction, use of the Fe(II) catalyst.

Table 1 Catalytic destruction of CWA simulants with *in situ* catalyst formation from air stable components showing the major products from each reaction

<table>
<thead>
<tr>
<th>Entry</th>
<th>IR·HCl</th>
<th>MX</th>
<th>CEES</th>
<th>Paraoxon-ethyl</th>
<th>Profenofos</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>IPr·HCl NiCl$_2$</td>
<td>EESS</td>
<td>CEES-O</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>IPr·HCl FeBr$_2$</td>
<td>EESS</td>
<td>CEES-O</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>IPr·HCl FeCl$_3$</td>
<td>CEES-O</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>IMes·HCl NiCl$_2$</td>
<td>EESS</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>IMes·HCl FeBr$_2$</td>
<td>EESS</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>IMes·HCl FeCl$_3$</td>
<td>CEES-O</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>ICy·HCl NiCl$_2$</td>
<td>EESS</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>ICy·HCl FeBr$_2$</td>
<td>BES</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>ICy·HCl FeCl$_3$</td>
<td>CEES-O</td>
<td></td>
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</tbody>
</table>

Reaction conditions used 1 µmol of NHC·HCl and metal salt, with 4 µmol of KO'Bu and 20 µmol of CWA simulant in 1 mL of MeCN at 80 °C.

NHC complexes of earth-abundant iron and nickel have shown widespread uses in homogeneous catalysis. Their combination with the simple bases KO'Bu was studied as a potential destruction method. Thus, a series of catalytic reactions in which the active catalyst is generated *in situ*, from the use of air stable components (NiCl$_2$, FeBr$_2$ and FeCl$_3$) with imidazolium salts (IPr·HCl, IMes·HCl and ICy·HCl) was carried out. Use of equimolar amounts of MCl$_n$ and IR·HCl with a fourfold excess of KO'Bu leads to the formation of NHC–MX$_n$ (where X = Cl or O'Bu) *in situ*, to which each of the chosen CWA simulants were then added 20-fold excess *(i.e. 5 mol% catalyst loading w.r.t. simulant)* and monitored over a period of 24 h at 80 °C using a combination of UV/vis, GC-MS and NMR spectroscopy.

In all cases catalytic destruction of the chosen simulants was observed after mild heating at 80 °C for 24 hours. In terms of CEES destruction, use of the Fe(III) complex results in oxidation to CEES-O as the major product (Table 1, entries 3, 6 and 9) whilst EESS and PCA were identified as the major products for Ni(II) and Fe(II) reactions (Table 1, entries 1, 2, 4, 5, and 7), except for FeBr$_2$ reactions in which osybis(ethylsulfane) BES was identified (Table 1, entry 8; Scheme 9). In the case of the nerve simulants P-OAr cleavage was identified as the major product through GC-MS analysis.

Attempts to render the (1–3)-V systems catalytic proved to be unsuccessful, but the reactions underline the capability of the oxidising metal in these CWA destructions.

Conclusions

Air- and moisture stable NHC complexes have been shown to be effective for the destruction of CWA simulants. The cooperation...
tive effect of both the NHC and metal centre is vital to the success of these decontamination reactions. Comparison of the simple commercially available imidazoline/imidazolium silver NHC complexes, (1–5)-Ag, these were found to provide efficient destruction under UV conditions in 5 h, primarily to the oxidation product, CEES-O, and also to the dehydrohalogenation product. The choice of metal centre is key for these transformations as reactions with complexes (1–3)-V provide complete destruction of CEES within 5 h and allowed for destruction of nerve simulants through cleavage of P-OAr bond to form substituted phenols. Preliminary studies using artificial sunlight (from a commercially available SAD lamp) also show reasonable levels of CEES decomposition within the same 5 h timeframe, presumably a result which could be improved with suitable ligand tuning.

Examination of the cooperative effect of metal centre and NHC through use of a hemi-labile bidentate aryloxide tethered NHC complex (6-M) shows clean destruction to E\text{VS} at 80 °C within a few hours. The rate of destruction is increased, and the reaction rendered catalytic in NHC within a few hours. The rate of destruction is increased, and the destruction of nerve simulants through cleavage of P-OAr bond to form substituted phenols. Preliminary studies using artificial sunlight (from a commercially available SAD lamp) also show reasonable levels of CEES decomposition within the same 5 h timeframe, presumably a result which could be improved with suitable ligand tuning.

Conflicts of interest

There are no conflicts to declare.

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Notes and references


