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The preparation and structure of Ge_3F_8 – a new mixed-valence fluoride of germanium, a convenient source of GeF_2^\dagger

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The new binary mixed-valence fluoride of germanium, Ge_3F_8 , has been obtained by heating GeF_4 with powdered Ge in an autoclave (390 K/4 bar/48 h). The structure contains pyramidal $\text{Ge}^{\text{II}}\text{F}_3$ and octahedral $\text{Ge}^{\text{IV}}\text{F}_6$ units, linked by fluoride bridges. The new compound is the missing member of the series $(\text{GeF}_2)_n\text{-GeF}_4$ ($n = 2, 4$, or 6). Sublimation of $(\text{GeF}_2)_n\text{-GeF}_4$ *in vacuo* provides a convenient source of GeF_2 in ca. 30% overall yield.

Although germanium is technologically very important both as the element and in oxide or chalcogenide compounds, with key applications in electronics, ceramics and optics,¹ its chemistry was neglected for many years compared with those of silicon and tin. It is now a very active area of main group chemistry and, in addition to the extensive chemistry of $\text{Ge}(\text{IV})$,² recent work has identified a large and complex coordination chemistry of $\text{Ge}(\text{II})$,^{2,3} the latter contrasting with the limited coordination chemistry of $\text{Si}(\text{II})$.² In Group 14 as well as the common tetrahalides MX_4 ($\text{M} = \text{Si}, \text{Ge}, \text{Sn}; \text{X} = \text{F-I}$),⁴ there are dihalides MX_2 ($\text{M} = \text{Ge}, \text{Sn}$), and the subhalides, GeBr and SnBr .⁵ Of these, the chemistry of GeF_2 has been very little explored since it is not readily available commercially and its preparation by repeatedly passing GeF_4 over heated germanium, is both inconvenient and time consuming,⁶ while the alternative method, involving the reaction of Ge with anhydrous HF in an autoclave, is hazardous. Both routes also require special equipment.⁷ A number of intermediate halides have also been identified.² The latter are of two types; the most common are those with element–element (E–E) bonds, including Si_2F_6 , Si_2Cl_6 , Si_3Cl_8 , $\text{Si}_6\text{Cl}_{14}$, Ge_2Cl_6 and $\text{Ge}_5\text{Cl}_{12}$,⁸ with structures analogous to the corresponding alkanes. Much

rarer, and limited to Ge and Sn, are a second group of mixed-valence materials, including Sn_3F_8 , Ge_5F_{12} , and Ge_7F_{16} , which are without direct E–E bonds, but are fluoride-bridged and contain distinct environments attributable to M^{II} and M^{IV} centres.^{9–11}

We are currently developing new routes for electrodeposition of p-block materials from non-aqueous media, using reagents including halometallate anions as the p-block element source,¹² and have recently reported the electrochemistry of $[\text{GeX}_3]^-$ ($\text{X} = \text{Cl}, \text{Br}$ or I) and $[\text{GeCl}_6]^{2-}$ in CH_2Cl_2 solution.¹³ During the course of this work we have extended our studies to the fluoride systems. We report here the preparation and characterisation of a new binary, mixed-valence fluoride of germanium and its use to provide a convenient route to GeF_2 .

Depending upon the experimental conditions, repeatedly passing GeF_4 at low pressure over heated germanium yields either GeF_2 ,⁶ or mixed valence $\text{Ge}^{\text{II}}\text{-Ge}^{\text{IV}}$ fluorides.^{10,11,14} Two of the latter identified by single crystal X-ray diffraction (XRD) studies are $\text{Ge}_5\text{F}_{12}^\dagger$ and Ge_7F_{16} ,^{10,11} which are members of the series $(\text{GeF}_2)_n\text{-GeF}_4$.¹⁴ These flow reactions are inconvenient and low yielding, hence we have investigated the reduction of GeF_4 with Ge powder in an autoclave under modest pressure (390 K/4 bar/48 h, see ESI†). Initial attempts at temperatures <370 K resulted in little reaction, but on increasing the temperature to 390 K/48 h, much of the GeF_4 was consumed (as indicated by the drop in pressure), and upon opening the autoclave in a glove-box, a mass of white microcrystalline material was found on the cooler lid. The crystals are extremely moisture sensitive, converting into a pool of liquid immediately on exposure to air. Single crystal X-ray diffraction data were collected from one of the small crystals and the structure solution identified this product as Ge_3F_8 , the missing third member of the series $(\text{GeF}_2)_n\text{-GeF}_4$, with $n = 2$. Unit cell measurements on several other crystals confirmed these as the same compound. Powder X-ray diffraction (PXRD) data were also collected on the bulk material and that showed smaller amounts of Ge_5F_{12} and Ge_7F_{16} , as well as traces of GeF_2 were also present. The simulated and experimental powder XRD data from this mixture are shown in the ESI.†

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† Electronic supplementary information (ESI) available: Experimental details for the syntheses of Ge_3F_8 and GeF_2 , and the PXRD data for all the products. Further details of the crystal structure investigation may be obtained from Fachinformationszentrum Karlsruhe, 76344 Eggenstein-Leopoldshafen, Germany (fax: (+49)7247-808-666; e-mail: crysdata@fiz-karlsruhe.de, http://www.fiz-karlsruhe.de/request_for_deposited_data.html) on quoting CSD number 427896. See DOI: 10.1039/c4dt02265c



Sublimation of the mixture (390 K/0.5 mm) gave ~30% yield of GeF_2 (based on elemental Ge used in the first step), which was identified by PXRD (see ESI†). Some involatile orange material (*cf.* ref. 6) was also formed.

Germanium difluoride has a polymeric chain structure based upon trigonal pyramidal GeF_3 units ($\text{Ge-F} = 1.79(2)$,

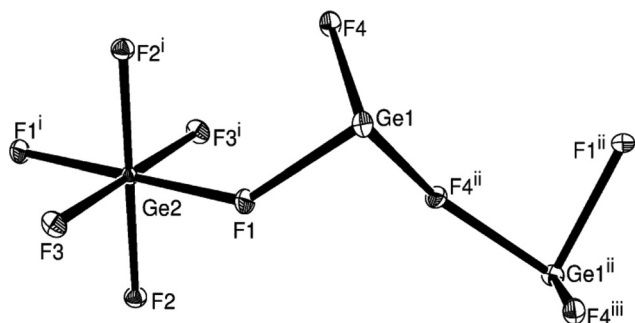


Fig. 1 The Ge^{II} and Ge^{IV} units in Ge_3F_8 with ellipsoids drawn at the 50% level. Selected bond lengths (\AA) and angles ($^\circ$): $\text{Ge2-F1} = 1.855(1)$, $\text{Ge2-F2} = 1.767(1)$, $\text{Ge2-F3} = 1.782(1)$, $\text{Ge1-F1} = 2.010(1)$, $\text{Ge1-F4}^{\text{ii}} = 1.938(1)$, $\text{Ge1-F4} = 1.980(1)$, $\text{F1-Ge1-F4} = 83.28(5)$, $\text{F4-Ge-F4}^{\text{ii}} = 86.35(3)$, $\text{F4}^{\text{ii}}-\text{Ge1-F1} = 85.42(6)$. Symmetry codes: (i) $1-x, 1-y, 1-z$; (ii) $0.5-x, -0.5+y, 1.5-z$; (iii) $x, -1+y, z$.

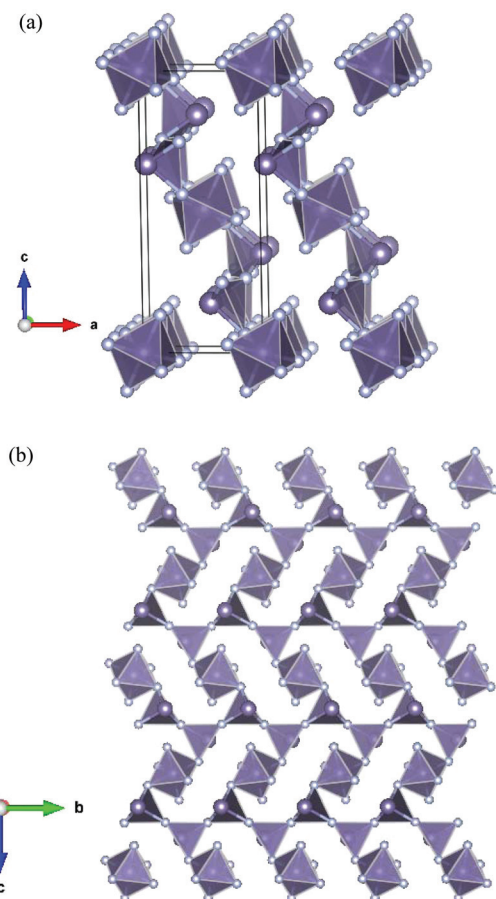


Fig. 2 The Ge_3F_8 structure viewed along: (a) the b axis to observe the sheets, and (b) the a axis, showing the connectivity within the sheets.

$1.91(2)$, $2.09(2)$ \AA), with a distant fourth fluoride at $2.57(2)$ \AA that cross-links the chains.¹⁵ The new preparation is a convenient way to obtain GeF_2 in useful quantity for further studies of its coordination and organometallic chemistry.

The single crystals of the mixed-valence Ge_3F_8 are isomorphous with Sn_3F_8 ,⁹ adopting the monoclinic space group $P2_1/n$. The structure is composed (Fig. 1) of slightly distorted GeF_6 octahedra with four terminal Ge-F bonds ($1.767(1)$, $1.782(1)$ \AA), and two slightly longer Ge-F bonds ($1.855(1)$ \AA) that are involved in bridging to the Ge^{II} units. The germanium (ii) core environment is trigonal pyramidal, composed of one terminal ($\text{Ge-F} = 1.938(1)$ \AA) and two bridging ($\text{Ge-F} = 1.980(1)$, $2.010(1)$ \AA) fluorides, one linked to Ge^{IV} and one to a second Ge^{II} centre. There are also longer $\text{Ge}^{\text{II}}\cdots\text{F}$ contacts (2.56 \AA), and if these are included, the germanium(ii) geometry is a distorted saw-horse shape, reminiscent of GeF_2 . Overall, the packing is best considered as sheets in the (101) planes (Fig. 2a), with each sheet being made up of puckered chains of GeF_3 units along [010] connected together by the GeF_6 octahedra (Fig. 2b).

Considering the structures of Ge_5F_{12} ¹⁰ and Ge_7F_{16} ,¹¹ the same basic building blocks are present (trigonal pyramidal GeF_3 and octahedral GeF_6), but as the F/Ge ratio declines, the

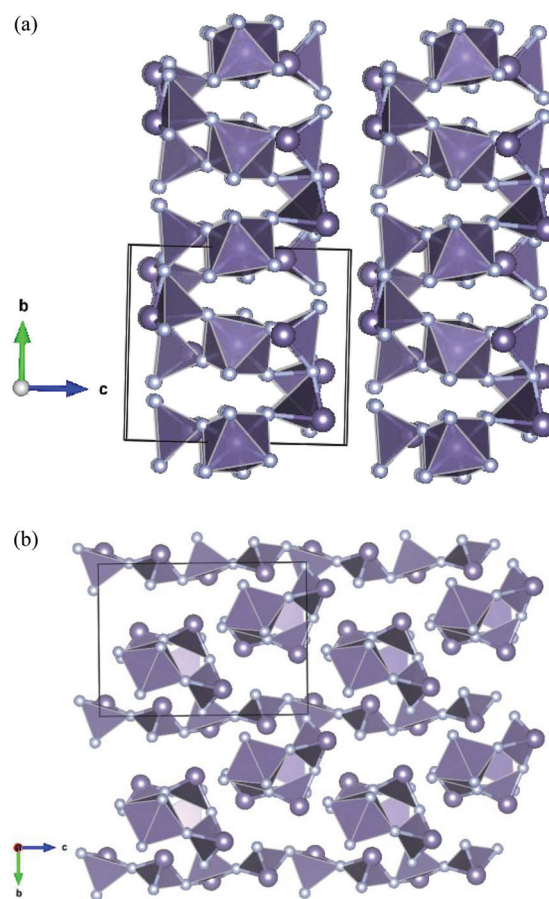


Fig. 3 (a) View of the structure of Ge_5F_{12} .¹⁰ (b) View of the structure of Ge_7F_{16} .¹¹



structures become more distorted to maintain the germanium coordination numbers. In Ge_5F_{12} , if we ignore the distant fourth fluoride at 2.44 Å, the GeF_3 trigonal pyramids ($\text{Ge}-\text{F} = 1.80(2), 1.99(2), 2.20(2)$ Å) form corrugated sheets in (001), based on GeF_6 octahedra linked to dimers of two corner-linked GeF_3 pyramids. As a consequence of the 4 : 1 $\text{Ge}^{\text{II}} : \text{Ge}^{\text{IV}}$ constitution, the GeF_6 units are linked to four dimers (rather than two as in Ge_3F_8) (Fig. 3a). The structure of Ge_7F_{16} is complicated in that there are seven distinct germanium sites,¹¹ but again, the building blocks are trigonal pyramidal GeF_3 and octahedral GeF_6 units. The structure is best described as chains of GeF_3 pyramids along [001] with side chains of four GeF_3 units terminated by a GeF_6 octahedron attached to every second GeF_3 of the main chain (Fig. 3b).

In conclusion, the missing member of the unique series of mixed-valence germanium fluorides $(\text{GeF}_2)_n\text{-GeF}_4$ ($n = 2, 4$, or 6) has been obtained by reaction of GeF_4 and Ge powder under modest pressure and temperature, its structure determined and the structural relationships within the series established. Sublimation of the $(\text{GeF}_2)_n\text{-GeF}_4$ *in vacuo* provides a convenient route to the previously rather inaccessible GeF_2 . Further work to explore the chemistry of GeF_2 formed by this route is underway and will be reported in due course.

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Notes and references

‡ Ge_5F_{12} was originally formulated as Ge_2F_5 ,¹⁴ the correct formula subsequently being established from the crystal structure determination.¹⁰

- (a) D. D. Vaughn II and R. E. Schaak, *Chem. Soc. Rev.*, 2013, **42**, 2861; (b) S. Raoux, W. Welnic and D. Ielmini, *Chem. Rev.*, 2010, **110**, 240; (c) D. V. Talapin, J. S. Lee, M. V. Kovalenko and E. V. Shevchenko, *Chem. Rev.*, 2010, **110**, 389.
- (a) J. Parr, in *Comprehensive Coordination Chemistry II*, ed. J. A. McCleverty and T. J. Meyer, Elsevier, Oxford, 2004, vol. 3, p. 545; (b) W. Levason, G. Reid and W. Zhang, *Coord. Chem. Rev.*, 2011, **255**, 1319; (c) N. N. Greenwood and A. Earnshaw, *Chemistry of the Elements*, Butterworth, Oxford, 2nd edn, 1997; (d) R. S. Ghadwal, H. W. Roesky, S. Merkel, J. Henn and D. Stalke, *Angew. Chem., Int. Ed.*, 2009, **48**, 5683; (e) A. C. Filippou, O. Chernov and G. Schnakenburg, *Angew. Chem., Int. Ed.*, 2009, **48**, 5687.
- For lead references on $\text{Ge}(\text{II})$ complexes see: (a) A. J. Arduengo III, H. V. Rasika Dias, J. C. Calabrese and F. Davidson, *Inorg. Chem.*, 1993, **32**, 1541; (b) P. A. Rugar, V. N. Staroverov, P. J. Ragona and K. M. Baines, *J. Am. Chem. Soc.*, 2007, **129**, 15138; (c) F. Cheng, A. L. Hector, W. Levason, G. Reid, M. Webster and W. Zhang, *Angew. Chem., Int. Ed.*, 2009, **48**, 5152; (d) F. Cheng, J. M. Dyke, F. Ferrante, A. L. Hector, W. Levason, G. Reid, M. Webster and W. Zhang, *Dalton Trans.*, 2010, **39**, 847; (e) F. Cheng, A. L. Hector, W. Levason, G. Reid, M. Webster and W. Zhang, *Inorg. Chem.*, 2010, **49**, 752; (f) J. England and K. Wiegardt, *Inorg. Chem.*, 2013, **52**, 10067; (g) P. A. Rugar, M. C. Jennings and K. M. Baines, *Organometallics*, 2008, **27**, 5043; (h) S. M. I. Al-Rafia, M. R. Momeni, R. McDonald, M. J. Ferguson, A. Brown and E. Rivard, *Angew. Chem., Int. Ed.*, 2013, **52**, 6390.
- A. K. Wolf, J. Glinnemann and M. U. Schmidt, *CrystEngComm*, 2008, **10**, 1364.
- (a) A. Schnepf and R. Köppe, *Z. Anorg. Allg. Chem.*, 2002, **628**, 2914; (b) C. Schrenk, R. Köppe, I. Schellenberg, R. Pöttgen and A. Schnepf, *Z. Anorg. Allg. Chem.*, 2009, **635**, 1541.
- N. Bartlett and K. C. Yu, *Can. J. Chem.*, 1961, **39**, 80.
- E. L. Muetterties, *Inorg. Chem.*, 1962, **1**, 342.
- (a) E. Hengge, in *Halogen Chemistry*, ed. V. Gutmann, Academic Press, NY, 1967, vol. 2, p. 169; (b) D. Shriver and W. L. Jolly, *J. Am. Chem. Soc.*, 1958, **80**, 6692; (c) I. R. Beattie, P. J. Jones, G. Reid and M. Webster, *Inorg. Chem.*, 1998, **37**, 6032.
- M. F. A. Dove, R. King and T. J. King, *J. Chem. Soc., Chem. Commun.*, 1973, 944.
- J. C. Taylor and P. W. Wilson, *J. Am. Chem. Soc.*, 1973, **95**, 1834.
- J. Köhler and J.-H. Chang, *Z. Anorg. Allg. Chem.*, 1997, **623**, 596.
- (a) P. N. Bartlett, D. Cook, C. H. de Groot, A. L. Hector, R. Huang, A. Jolleys, G. P. Kissling, W. Levason, S. J. Pearce and G. Reid, *RSC Adv.*, 2013, **3**, 15645; (b) P. N. Bartlett, D. A. Cook, M. W. George, A. L. Hector, J. Ke, W. Levason, G. Reid, D. C. Smith and W. Zhang, *Phys. Chem. Chem. Phys.*, 2014, **16**, 9202.
- P. N. Bartlett, C. Y. Cummings, W. Levason, D. Pugh and G. Reid, *Chem. – Eur. J.*, 2014, **20**, 5019.
- G. P. Adams, J. L. Margrave and P. W. Wilson, *J. Inorg. Nucl. Chem.*, 1973, **33**, 1301.
- (a) J. Trotter, M. Akhtar and N. Bartlett, *J. Chem. Soc. A*, 1966, 30; (b) G. Denes, *J. Solid State Chem.*, 1989, **78**, 52.

