

Synthesis, properties and structures of NbOF₃ complexes and comparisons with NbOCl₃ analogues†

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The first series of complexes of niobium(v) oxide trifluoride, [NbOF₃(OPR₃)₂] (R = Me or Ph), [NbOF₃(dppmO₂)] (dppmO₂ = Ph₂P(O)CH₂P(O)Ph₂), [NbOF₃(dmsO)₂], [NbOF₃(tmeda)] (tmeda = Me₂N-(CH₂)₂NMe₂) and [NbOF₃(diimine)] (diimine = 2,2'-bipy, 1,10-phen) have been prepared, either by reaction of the corresponding complexes of NbF₅ and hexamethyldisiloxane (HMDSO) in CH₂Cl₂-MeCN solution, or directly from NbF₅, ligand and HMDSO. They were characterised by IR, ¹H, ³¹P{¹H} and ¹⁹F{¹H} NMR spectroscopy, and X-ray crystal structures are reported for [NbOF₃(OPR₃)₂] (R = Me or Ph) and [NbOF₃(dppmO₂)]. Complexes of NbOCl₃, [NbOCl₃(OPPh₃)₂], [NbOCl₃(dppmO₂)], [NbOCl₃(dppeO₂)] (dppeO₂ = Ph₂P(O)(CH₂)₂P(O)Ph₂), [NbOCl₃(tmeda)] and [NbOCl₃(diimine)] were made from NbCl₅ and HMDSO in MeCN (which forms [NbOCl₃(MeCN)₂] *in situ*), followed by addition of the neutral ligand. Their properties are compared with the oxide fluoride analogues. X-ray structures are reported for [NbOCl₃(dppmO₂)], [NbOCl₃(dppeO₂)], [NbOCl₃(tmeda)] and [NbOCl₃(2,2'-bipy)]. The synthesis and spectroscopic characterisation of [MF₅L] (M = Nb or Ta; L = OPR₃, OAsPh₃) and [MF₄(diimine)₂][MF₆] are also described, and the key properties of the four series of complexes compared.

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Introduction

The fluorides and oxide fluorides of early transition metals in high oxidation states are strong Lewis acids and form a substantial range of complexes with F⁻ and with hard N- or O-donor ligands, whilst their more limited chemistry with soft donor ligands (P, S *etc.*) sometimes includes redox chemistry at the metal centre and oxidation/fluorination of the heteroatom donor, in addition to adduct formation.¹ The properties of the metal centre are significantly altered by the small very electronegative fluoride ligands, and the chemistry of these fluorides/oxide fluorides is often very different to that of the chloride analogues.¹

Within Group V, the coordination chemistry of the oxide fluorides VOF₃,² and VO₂F₂³ has been studied in some detail recently, whilst that of VF₅ is completely unexplored. In contrast, an extensive series of complexes of MF₅ (M = Nb or Ta) with both hard N- and O-donor^{1,4} and soft S-donor⁵ ligands

are known, but the oxide-fluorides, MOF₃, are intractable and very little studied.^{6,7} Here we report the synthesis, spectroscopic and structural characterisation of a series of adducts of NbOF₃. Complexes of NbOCl₃ have long been known, originally obtained by adventitious hydrolysis, or O-abstraction from the solvent or ligand in reactions of NbCl₅.⁸ More systematic syntheses used the reaction of NbCl₅ with siloxanes or occasionally direct reaction with the polymeric NbOCl₃,⁹ and selected examples have been re-examined in the present work to provide comparisons with the NbOF₃ complexes. NbOF₃ is obtained by heating NbF₅ with NbO₂F in argon, and has a structure based upon six-coordinate niobium (SnF₄ type), but the O/F disorder is only partially understood.⁶ It decomposes on heating above 180 °C, hydrolyses in air in a few hours, and is insoluble in organic solvents, making it completely unsuitable as a synthon to explore the coordination chemistry. TaOF₃, which is formed similarly from TaO₂F and TaF₅, is also disordered and unreactive.⁶

We describe here a convenient alternative route to NbOF₃ complexes involving F/O exchange from the corresponding NbF₅ adducts, using hexamethyldisiloxane (HMDSO). Similar halogen/oxygen exchange has proved to be a useful route for the preparation of complexes of polymeric oxide halides, including, for example, MO₂X₂ (M = Mo or W; X = Cl or Br),¹⁰ although it has rarely been used for oxide fluoride complexes.¹

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† Electronic supplementary information (ESI) available: The crystallographic data and selected bond lengths and angles for [Me₃TACNH]₂[NbOCl₅] are also available in the ESI. CCDC 973570–973577. For ESI and crystallographic data in CIF or other electronic format see DOI: 10.1039/C3DT53322K



Table 1 Comparison of spectroscopic data

Complex	$^{19}\text{F}\{^1\text{H}\}^a$	$^{31}\text{P}\{^1\text{H}\}^a$	$\nu(\text{P/AsO})^b$	$\nu(\text{Nb/TaX})^b/\text{cm}^{-1}$	$\nu(\text{NbO})^b/\text{cm}^{-1}$
$[\text{NbF}_5(\text{OPPh}_3)]$	161.8(s, [F]), 128.6(s, [4F])	53.9 ^c	1061(vs) ^c	624(sh), 608(vs, br)	—
$[\text{NbF}_5(\text{OPMe}_3)]$	157.6(s, [F]), 134.5(s, [4F])	75.6 ^d	1092(vs) ^d	615(vs, br), 582(m)	—
$[\text{NbF}_5(\text{OAsPh}_3)]$	145.0(s, [F]), 110.5(s, [4F])	—	845(s)	620(sh), 600(vs, br)	—
$[\text{NbF}_4(2,2'\text{-bipy})_2][\text{NbF}_6]$	139.7(s, [4F]), 103.2 (10 lines, $J = 335 \text{ Hz}$)	—	—	615(vs), 603(s), 585(vs)	—
$[\text{NbF}_4(1,10\text{-phen})_2][\text{NbF}_6]$	138.0(s, [4F]), 103.4 (10 lines, $J = 335 \text{ Hz}$)	—	—	608(vs), 586(vs), 565(sh)	—
$[\text{NbOF}_3(\text{OPPh}_3)_2]$	49.5(s, [F]), 37.8(s, [2F])	45.0(s, [P]), 36.0(s, [P])	1155(m), 1067(s)	602(m), 579(s)	941(s)
$[\text{NbOF}_3(\text{OPMe}_3)_2]$	41.5(s, [F]), 30.6(s, [2F])	67.1(s, [P]), 53.3(s, [P])	1140(m), 1087(s)	614(s), 582(m), 555(s)	958(s)
$[\text{NbOF}_3(\text{dppmO}_2)]$	55.7(s, [F]), 36.4(s, [2F])	46.6(d, [P]) ^e , 36.8(d, [P]) ^f	1156(s), 1088(s) ^f	608(vs), 582(s)	944(s)
$[\text{NbOF}_3(\text{dmso})_2]$	50.4(s, [F]), 38.0(s, [2F])	—	—	590(s), 564(s)	920(s)
$[\text{NbOF}_3(2,2'\text{-bipy})]$	49.0(s, [F]), 42.8(s, [2F])	—	—	612(vs), 579(s)	959(s)
$[\text{NbOF}_3(1,10\text{-phen})]$	Insol	—	—	610(sh), 594(s), 583(s)	970(s)
$[\text{NbOF}_3(\text{tmeda})]$	Insol	—	—	587(s), 557(s)	920(s)
$[\text{TaF}_5(\text{OPPh}_3)]$	84.2(s, [F]), 54.7(s, [4F])	53.2(s)	1078(s)	617(sh), 592(vs, br)	—
$[\text{TaF}_5(\text{OPMe}_3)]$	82.5(s, [F]), 55.9(s, [4F])	76.9(s)	1092(vs)	601(sh), 583(vs, br)	—
$[\text{TaF}_5(\text{OAsPh}_3)]$	62.5(s, [F]), 48.6(s, [4F])	—	845(s)	617(sh), 592(vs, br)	—
$[\text{TaF}_4(2,2'\text{-bipy})_2][\text{TaF}_6]$	68.1(s, [4F]), 38.0(s, [6F])	—	—	605(sh), 581(vs)	—
$[\text{TaF}_4(1,10\text{-phen})_2][\text{TaF}_6]$	66.1(s, [4F]), 37.9(s, [6F])	—	—	605(sh), 576(s)	—
$[\text{NbOCl}_3(\text{OPPh}_3)_2]$	—	50.0(s, [P]), 38.8(s, [P])	1159(s), 1074(s)	325(s), 294(m)	936(s)
$[\text{NbOCl}_3(\text{dppmO}_2)]$	—	48.5(d, [P]), 36.8(d, [P])	1157(s), 1095(s)	327(s), 296(m)	928(s)
$[\text{NbOCl}_3(\text{dpppeO}_2)]$	—	56.7(s, [P]), 44.9(s, [P])	1172(s), 1066(s)	320(s), 293(w)	943(s)
$[\text{NbOCl}_3(2,2'\text{-bipy})]$	—	—	—	349(s), 338(s)	943(s)
$[\text{NbOCl}_3(1,10\text{-phen})]$	—	—	—	338(br)	944(s)
$[\text{NbOCl}_3(\text{tmeda})]$	—	—	—	341(s), 320(sh)	945(s)

^a $\text{CH}_2\text{Cl}_2\text{-CD}_2\text{Cl}_2$ solution 298 K. ^b Nujol mull. ^c Ligand $\delta(\text{P}) = +28.0$, $\nu(\text{PO}) = 1195$. ^d Ligand $\delta(\text{P}) = +35.0$, $\nu(\text{PO}) = 1160$. ^e Ligand $\delta(\text{P}) = +25.0$, $\nu(\text{PO}) = 1187$. ^f Ligand $\delta(\text{P}) = +35.0$, $\nu(\text{PO}) = 1174 \text{ cm}^{-1}$ data from ref. 24.

Results and discussion

MF₅ complexes

The reaction of NbF_5 with OPR_3 (R = Me or Ph) in rigorously anhydrous CH_2Cl_2 solution gave $[\text{NbF}_5(\text{OPR}_3)]$ as white powders, easily soluble in halocarbon solvents. The complexes have been mentioned before, but with limited characterisation data.^{4d,11} The $^{19}\text{F}\{^1\text{H}\}$ NMR spectra show two singlets with relative intensities 1 : 4 and the $^{31}\text{P}\{^1\text{H}\}$ NMR spectra are singlets with large, high frequency coordination shifts (Table 1), consistent with their formulation as octahedral monomers. They also show broad singlet ^{93}Nb NMR resonances[†] $\delta \sim -1530$. The IR spectra show strong terminal Nb–F vibrations in the range 630–570 cm^{-1} , and $\nu(\text{PO})$ are markedly lower than the “free” ligand values (Table 1). The $[\text{NbF}_5(\text{OAsPh}_3)]$ was made similarly from cold (0 °C) CH_2Cl_2 solution, but must be isolated rapidly, otherwise significant decomposition occurs, forming Ph_3AsF_2 ($\delta(^{19}\text{F}) = -89.4$),^{3a} $[\text{NbF}_6]^-$ (identified by *in situ* ^{19}F NMR spectroscopy)^{5a} and other unidentified products. The tantalum complexes $[\text{TaF}_5(\text{OPR}_3)]$ and $[\text{TaF}_5(\text{OAsPh}_3)]$ were prepared similarly, and show corresponding trends in their spectroscopic properties (Table 1). However, the large quadrupole moment of ^{181}Ta ($I = 7/2$, $Q = 3 \times 10^{-28} \text{ m}^2$) results in fast quadrupolar relaxation and hence ^{181}Ta NMR resonances are not observable.

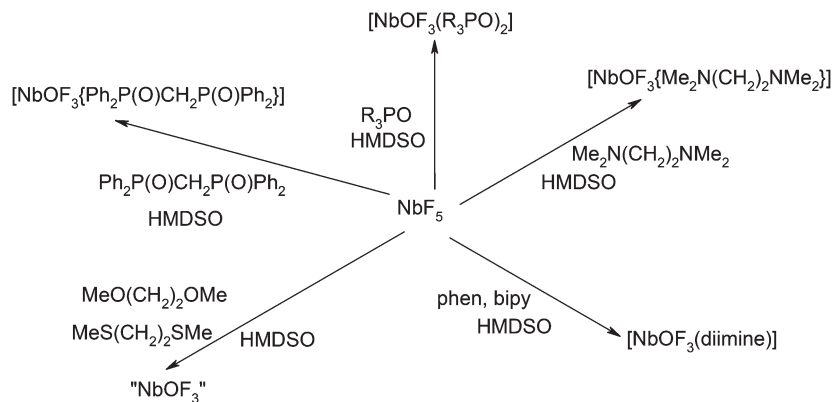
[†] ^{93}Nb 100% abundance, $I = 9/2$, $\mathcal{E} = 24.44 \text{ MHz}$, $Q = -0.2 \times 10^{-28} \text{ m}^2$, $D_c = 2740$ is one of the more sensitive nuclei and, despite the medium size quadrupole moment, is readily observed in many systems. The zero reference is $[\text{NbCl}_6]^-$ in MeCN.

The reaction of NbF_5 with 2,2'-bipyridyl or 1,10-phenanthroline in CH_2Cl_2 solution gave very poorly soluble complexes with a 1 : 1 NbF_5 : diimine composition, originally assumed¹² to be seven-coordinate monomers. We found them to be sufficiently soluble in CD_2Cl_2 solution to obtain ^1H and ^{19}F $\{^1\text{H}\}$ NMR spectra after long accumulations, which show equivalent pyridyl rings and two ^{19}F resonances with intensity ratio of 2 : 3. The more intense resonance is the characteristic 10 line multiplet of $[\text{NbF}_6]^-$,^{5a} leading to the revised formulation, $[\text{NbF}_4(\text{diimine})_2][\text{NbF}_6]$, with an eight-coordinate cation, as found in other adducts with chelating bidentate ligands.¹ The $[\text{TaF}_4(\text{diimine})_2][\text{TaF}_6]$ were made similarly and were even less soluble. Eight-coordination is also found in the diimine complexes of Zr and Hf (M'), $[\text{M}'\text{F}_4(\text{diimine})_2]$.¹³ The very poor solubility of the isolated $[\text{MF}_4(\text{diimine})_2][\text{MF}_6]$ complexes made them unsuitable as synthons for the O/F exchange reactions, and hence studies were switched to using *in situ* syntheses, although the data on the isolated MF₅ adducts are useful for comparison purposes (Table 1).

NbOF₃ complexes

Treatment of an anhydrous CH_2Cl_2 solution of $[\text{NbF}_5(\text{OPPh}_3)]$ with one mol. equivalent of OPPh_3 , followed by one mol. equivalent of HMDSO, resulted in slow formation of a white precipitate, identified as $[\text{NbOF}_3(\text{OPPh}_3)_2]$. We subsequently found that “one-pot” syntheses were possible and more convenient, although the sequence of addition of the reactants and the time-scales are key to obtaining pure complexes (Scheme 1). The addition of NbF_5 and two mol. equivalents of OPPh_3 to anhydrous CH_2Cl_2 yields a colourless solution,





Scheme 1 Synthesis of NbOF₃ adducts.

which was stirred for 20 min. and then one mol. equivalent of HMDSO and a small amount of MeCN were added. After 24 h the mixture, now containing much white precipitate, was concentrated *in vacuo*, and the [NbOF₃(OPPh₃)₂] isolated. If the HMDSO was added before, or simultaneously with, the OPPh₃, very impure products resulted, and several hours seem necessary to complete the O/F exchange. The role of the MeCN is not entirely clear, but its presence seems necessary to obtain pure samples from the *in situ* preparations. In the syntheses of [WO₂Cl₂{RS(CH₂)₂SR}] from WCl₆ or WOCl₄, RS(CH₂)₂SR and HMDSO, use of MeCN-CH₂Cl₂ as solvent prevents the precipitation of polymeric WO₂Cl₂, by forming the nitrile adduct *in situ*.^{10c} While a similar role may be present in the niobium systems, we note that attempts to isolate nitrile complexes failed (see below). The complexes [NbOF₃(OPMe₃)₂] and [NbOF₃(dppmO₂)] were prepared similarly to [NbOF₃(OPPh₃)₂], but all attempts to obtain [NbOF₃(OAsPh₃)₂] gave mixtures containing [NbF₅(OAsPh₃)], [NbF₆]⁻ and Ph₃AsF₂ (identified based upon *in situ* ¹⁹F and ⁹³Nb NMR spectra). [NbOF₃(OAsPh₃)] was originally reported to be formed from adding OAsPh₃ to a solution of Nb₂O₅ in conc. aqueous HF, although identified only by an IR spectrum.^{7b} Using a 4 : 2 : 1 molar ratio of OPPh₃ : HMDSO : NbF₅ in CH₂Cl₂-MeCN resulted only in isolation of [NbOF₃(OPPh₃)₂], further O/F exchange did not occur. The complex [NbOF₃(dmsO)] was also isolated in high yield from reaction of NbF₅, dmsO and HMDSO. As noted above, the very poor solubility of [NbF₄(diimine)₂][NbF₆] made it impossible to redissolve them in CH₂Cl₂ for conversion to oxide-fluoride complexes. However, combination of the diimine and NbF₅ in a large volume of CH₂Cl₂ (which gave a opalescent solution), followed by addition of HMDSO, did give [NbOF₃(diimine)]. The [NbOF₃(tmeda)] was made in high yield as an air-stable white powder by sequential reaction of NbF₅, tmeda and HMDSO.

In contrast, reaction of NbF₅ with ethers, including thf and MeO(CH₂)₂OMe or with MeCN in CH₂Cl₂ followed by addition of HMDSO, gave white insoluble powders, which showed only traces of organic ligand in the IR spectra, and had very broad, ill-defined bands in the IR spectra, similar to those reported for NbOF₃.^{6,7a} The attempted reaction of NbF₅, MeS(CH₂)₂SMe

and HMDSO also failed. Ether, nitrile and thioether adducts of NbF₅ are well characterised,^{1,4,5} but it seems that these ligands are too weakly bound to the “NbOF₃” to prevent polymerisation and precipitation of ligand-free NbOF₃. Similar behaviour was observed with VO₂F,³ and the niobium system seems to be a further example of the metal centre preferring to form oxide/fluoride bridges rather than coordinate to weak, neutral donor groups.¹ Thus far, attempts to isolate TaOF₃ complexes from TaF₅, ligand (ligand = OPR₃, dmsO or 2,2'-bipy) and HMDSO under similar reaction conditions, have been unsuccessful.

The solid [NbOF₃(OPR₃)₂], [NbOF₃(dmsO)] and [NbOF₃(dppmO₂)] complexes are white powders, relatively air-stable in the solid state (some appear hygroscopic on prolonged exposure), although hydrolysed by wet solvents. They are easily soluble in CH₂Cl₂, whereas the [NbOF₃(diimine)] are very poorly soluble, and [NbOF₃(tmeda)] is insoluble. The ¹H and ³¹P{¹H} NMR spectra (Table 1) of [NbOF₃(OPMe₃)₂] show two phosphine oxide environments, and the ¹⁹F{¹H} NMR spectrum contains two singlets with integrals in the ratio 1 : 2, which is consistent with *mer*-fluorines and one OPMe₃ *trans* to O and one *trans* to F. Attempts to record a ⁹³Nb NMR spectrum were unsuccessful (an effect observed for all the NbOF₃ adducts), contrasting with the ready observation of resonances from the NbF₅ adducts described above. The low symmetry at the niobium centre will result in a large electric field gradient, and unobservably broad lines due to fast quadrupolar relaxation. The different *trans*-influences of Nb-F and Nb=O groups in these complexes are also shown by the difference in ³¹P chemical shifts for the *trans* disposed OPMe₃ ligands (~14 ppm), and similar differences are seen in the ν(PO) frequencies in the IR spectra which differ by >50 cm⁻¹. A strong band in the range 970–920 cm⁻¹ is assignable to the terminal Nb=O vibrations.

Confirmation of the geometry of [NbOF₃(OPMe₃)₂] comes from the X-ray crystal structure (Fig. 1).

There is no evidence in this molecule for O/F disorder in plane, which is a common problem in this area of chemistry (*cf.* [VOF₃(OPPh₃)₂]^{2b}). The niobium is in a distorted octahedral environment with the axial F-Nb-F unit bent away from the



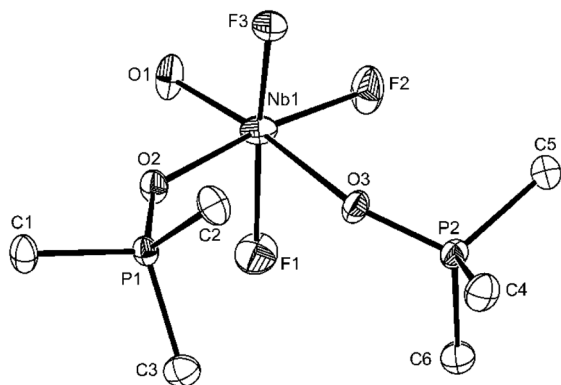


Fig. 1 The structure of the Nb1 centred molecule in $[\text{NbO-F}_3(\text{OPMe}_3)_2] \cdot 1/3\text{CH}_2\text{Cl}_2$ showing the atom labelling scheme. Displacement ellipsoids are drawn at the 50% probability level and H-atoms and the solvate molecule are omitted for clarity. The second Nb2 centred molecule is similar with the third (Nb3) being disordered. Selected bond lengths (Å) and angles ($^\circ$): Nb1–O1 = 1.773(2), Nb1–F2 = 1.868(2), Nb1–F3 = 1.9184(19), Nb1–F1 = 1.935(2), Nb1–O2 = 2.104(2), Nb1–O3 = 2.205(2), P1–O2 = 1.526(2), P2–O3 = 1.521(2), O1–Nb1–F2 = 98.58(10), O1–Nb1–F3 = 97.00(11), F2–Nb1–F3 = 92.20(10), O1–Nb1–F1 = 95.09(11), F2–Nb1–F1 = 92.72(10), F3–Nb1–F1 = 166.12(9), O1–Nb1–O2 = 91.75(9), F3–Nb1–O2 = 86.21(9), F1–Nb1–O2 = 86.63(9), F2–Nb1–O3 = 87.90(8), F3–Nb1–O3 = 84.76(9), F1–Nb1–O3 = 82.46(9), O2–Nb1–O3 = 81.80(8).

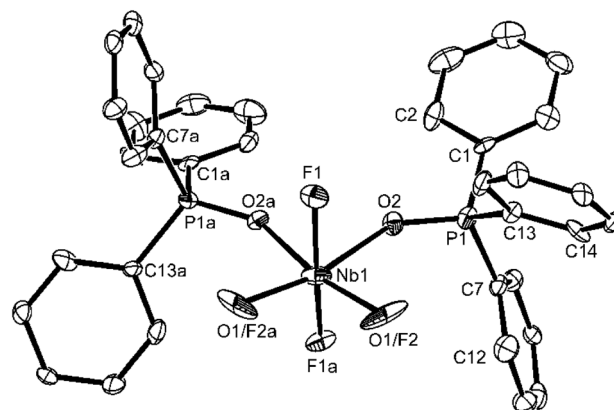


Fig. 2 The structure of $[\text{NbOF}_3(\text{OPPh}_3)_2]$ showing the atom numbering scheme. The phenyl rings are numbered cyclically starting at the *ipso* C atom. Ellipsoids are drawn at the 50% probability level and H atoms are omitted for clarity. The molecule has two-fold symmetry. Notice the disorder at the atom site O1/F2. Symmetry operation: $a = 1 - x, -y, z$. Selected bond lengths (Å) and angles ($^\circ$): Nb1–O1 = 1.850(4), Nb1–F2 = 1.850(4), Nb1–F1 = 1.932(4), Nb1–O2 = 2.189(4), P1–O2 = 1.532(4), O1–Nb1–F2 = 108.2(4), O1–Nb1–F1 = 92.06(19), F2–Nb1–F1 = 95.36(18), F1–Nb1–F1a = 167.3(2), O1–Nb1–O2 = 86.8(2), F1–Nb1–O2 = 84.23(16), O2–Nb1–O2 = 78.3(2).

oxido-ligand. The Nb–F_{trans F} are longer than Nb–F_{trans O} by ~ 0.06 Å and the Nb=O of 1.773(2) Å is consistent with the expected multiple bond character. The Nb–O(P)_{trans F} distances of 2.104(2) Å and Nb–O(P)_{trans O} = 2.205(2) Å show the disparate effects of the *trans* donor and parallel the spectroscopic evidence. Curiously, $d(\text{P}=\text{O})$ in the two phosphine oxide ligands are only slightly different. The spectroscopic data on $[\text{NbO-F}_3(\text{OPPh}_3)_2]$ (Table 1) are very similar to those of the OPMe_3 complex discussed, but in this case the X-ray structure (Fig. 2) shows F/O disorder *trans* to OPPh_3 , and the bond length and angle data are correspondingly unreliable, although the identity of the complex is confirmed.

The structural parameters of $[\text{NbOF}_3(\text{dppmO}_2)]$ are generally similar to those already discussed above, and this complex seems free of O/F disorder (Fig. 3).

The $[\text{NbOF}_3(\text{tmeda})]$ is insoluble in non-coordinating solvents and MeCN, and is partially decomposed by dmf or dmsu which prevented solution measurements. However, the $[\text{NbOF}_3(\text{diimine})]$, although very poorly soluble in chlorocarbons or MeCN (a property shared with the NbF_5 analogues above, and also the ZrF_4 , HfF_4 , VOF_3 and VO_2F diimine complexes),^{2,3,13} gave ^1H NMR spectra showing inequivalent pyridyl rings, and hence that the diimine was *trans* to O/F. The $^{19}\text{F}\{^1\text{H}\}$ NMR spectrum of $[\text{NbOF}_3(2,2'\text{-bipy})]$ (Table 1) shows two resonances in the ratio 1 : 2 consistent with a *mer* arrangement of the fluorines, and the chemical shifts are ~ 100 ppm to low frequency of those observed for the $[\text{NbF}_4(\text{diimine})_2]^+$. The $[\text{NbOF}_3(1,10\text{-phen})]$ was very poorly soluble in weakly coordinating solvents and a convincing $^{19}\text{F}\{^1\text{H}\}$ NMR spectrum was not obtained. The diimine complexes are readily hydrolysed in

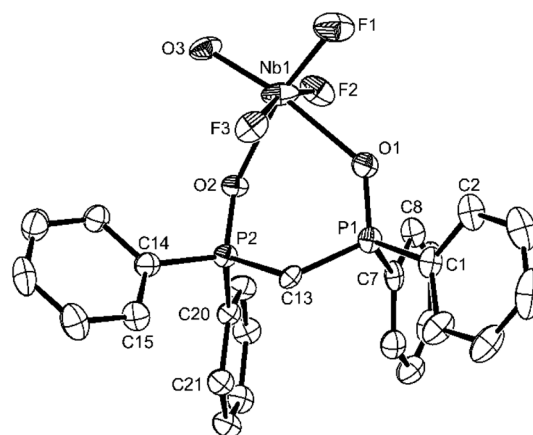
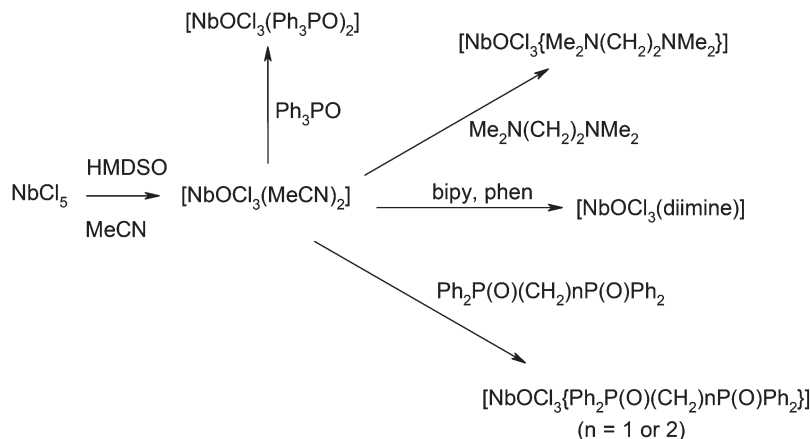


Fig. 3 The structure of $[\text{NbOF}_3(\text{dppmO}_2)]$ showing the atom labelling scheme. Displacement ellipsoids are drawn at the 50% probability level and H-atoms are omitted for clarity. Selected bond lengths (Å) and angles ($^\circ$): Nb1–O3 = 1.782(4), Nb1–F1 = 1.850(3), Nb1–F2 = 1.912(3), Nb1–F3 = 1.970(3), Nb1–O2 = 2.171(3), Nb1–O1 = 2.257(4), P1–O1 = 1.508(4), P2–O2 = 1.509(3), O3–Nb1–F1 = 100.96(17), O3–Nb1–F2 = 98.04(16), F1–Nb1–F2 = 95.28(15), O3–Nb1–F3 = 95.34(16), F1–Nb1–F3 = 94.41(15), O3–Nb1–O2 = 91.31(15), F2–Nb1–O2 = 83.99(13), F3–Nb1–O2 = 83.24(13), F1–Nb1–O1 = 87.03(15), F2–Nb1–O1 = 84.16(14), F3–Nb1–O1 = 80.84(13), O2–Nb1–O1 = 80.66(13), F2–Nb1–F3 = 161.67(13).

solution in CH_2Cl_2 or MeCN forming $[\text{NbF}_6]^-$ ions, based upon ^{19}F NMR evidence and also shown by attempts to obtain crystals of $[\text{NbOF}_3(2,2'\text{-bipy})]$ for an X-ray study which produced a few poor quality crystals of $[2,2'\text{-bipyH}][\text{NbF}_6]$. The solids also hydrolyse slowly on exposure to the atmosphere.



Scheme 2 Synthesis of NbOCl_3 adducts.

NbOCl_3 complexes

Solid NbOCl_3 contains dimeric $[\text{Cl}_2\text{Nb}(\text{O})(\mu\text{-Cl})_2\text{Nb}(\text{O})\text{Cl}_2]$ units linked into chains *via* unsymmetrical oxide bridges, giving six-coordinate niobium.¹⁴ The syntheses of the $[\text{NbOCl}_3(\text{L-L})]$ ($\text{L-L} = 2,2'$ -bipy, 1,10-phen, dppmO_2 , dppeO_2 , tmeda and $2 \times \text{OPPh}_3$) were carried out in anhydrous MeCN solution, with the reversed order of reagent addition to that used for the oxide-fluoride syntheses, *i.e.* reacting NbCl_5 with HMDSO to form 'NbOCl₃' *in situ*, followed by addition of the neutral ligand (Scheme 2). The initially yellow solution of NbCl_5 in MeCN rapidly pales on addition of HMDSO, indicating formation of $[\text{NbOCl}_3(\text{MeCN})_2]$ *in situ*,^{9b,15} which was converted into near colourless $[\text{NbOCl}_3(\text{L-L})]$ upon addition of the neutral ligand. Once isolated, the $[\text{NbOCl}_3(\text{tmeda})]$ is essentially insoluble in non-coordinating solvents, although crystals were grown adventitiously from the reaction filtrate. The other complexes are soluble in CH_2Cl_2 or MeCN. The IR spectra of the complexes (Table 1) show strong $\nu(\text{Nb}=\text{O})$ in the region $920\text{--}950\text{ cm}^{-1}$ and $\nu(\text{NbCl})$ $290\text{--}350\text{ cm}^{-1}$ with disparate $\nu(\text{P}=\text{O})$ vibrations for the phosphine oxide groups *trans* to Cl and *trans* to O. In solution, the ^1H and $^{31}\text{P}\{^1\text{H}\}$ NMR spectra of $[\text{NbOCl}_3(\text{L-L})]$ ($\text{L-L} = \text{dppmO}_2$, dppeO_2 , $2 \times \text{OPPh}_3$) show the expected inequivalence of the neutral donor groups, but attempts to record ^{93}Nb spectra were unsuccessful; as with the oxide-fluorides this is attributed to fast quadrupolar relaxation in the low symmetry electric fields.

X-Ray crystal structures were obtained for five of the complexes. The structure of $[\text{NbOCl}_3(\text{OPPh}_3)_2]$ has been reported previously and shows¹⁶ *mer*-chlorines, and *cis* OPPh_3 groups, with O/Cl disorder *trans* to OPPh_3 . The crystal structures of the two diphosphine dioxide complexes (Fig. 4 and 5) show $d(\text{Nb}=\text{O})$ slightly shorter by $\sim 0.1\text{ \AA}$ compared to the oxide fluoride complexes, but with similarly disparate $d(\text{Nb}-\text{O}(\text{P}))$ suggesting the *trans* influence of F and Cl are similar in these complexes. The $d(\text{Nb}=\text{O})$ and $d(\text{Nb}-\text{Cl})$ distances in a range of NbOCl_3 adducts cover quite a narrow range,^{8,9,15,16} suggesting that these are the dominant bonding interactions, with the neutral ligands completing the coordination sphere, but having little influence on the $\text{Nb}=\text{O}$ and $\text{Nb}-\text{Cl}$ bonds.

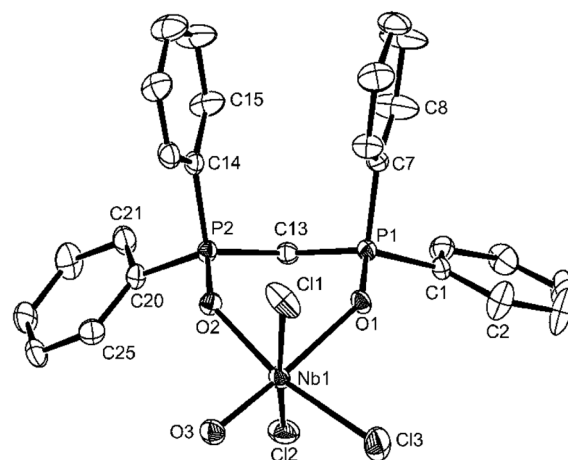


Fig. 4 The structure of $[\text{NbOCl}_3(\text{dppmO}_2)] \cdot n\text{MeCN}$ showing the atom labelling scheme. Displacement ellipsoids are drawn at the 50% probability level and H-atoms are omitted for clarity. The solvate acetonitrile is also omitted. The phenyl rings are numbered cyclically starting at the *ipso*-C atom. Selected bond lengths (\AA) and angles ($^\circ$): $\text{Nb1}-\text{O3} = 1.706(3)$, $\text{Nb1}-\text{O2} = 2.095(3)$, $\text{Nb1}-\text{O1} = 2.266(3)$, $\text{Nb1}-\text{Cl3} = 2.3463(13)$, $\text{Nb1}-\text{Cl1} = 2.3815(13)$, $\text{Nb1}-\text{Cl2} = 2.4203(12)$, $\text{O3}-\text{Nb1}-\text{O2} = 94.47(12)$, $\text{O2}-\text{Nb1}-\text{O1} = 80.48(10)$, $\text{O3}-\text{Nb1}-\text{Cl3} = 98.84(10)$, $\text{O1}-\text{Nb1}-\text{Cl3} = 86.17(7)$, $\text{O3}-\text{Nb1}-\text{Cl1} = 97.53(10)$, $\text{O2}-\text{Nb1}-\text{Cl1} = 86.85(8)$, $\text{O1}-\text{Nb1}-\text{Cl1} = 84.56(7)$, $\text{Cl3}-\text{Nb1}-\text{Cl1} = 92.45(6)$, $\text{O3}-\text{Nb1}-\text{Cl2} = 93.91(10)$, $\text{O2}-\text{Nb1}-\text{Cl2} = 85.00(8)$, $\text{O1}-\text{Nb1}-\text{Cl2} = 83.41(7)$, $\text{Cl3}-\text{Nb1}-\text{Cl2} = 92.98(5)$, $\text{Cl1}-\text{Nb1}-\text{Cl2} = 166.43(4)$.

The structure of $[\text{NbOCl}_3(\text{tmeda})]$ (Fig. 6) shows the same features as those of the oxygen donor complexes, although the carbon atoms about N2 show some disorder; there is no evidence for O/Cl disorder. The dimensions in the structure of $[\text{NbOCl}_3(2,2'\text{-bipy})]$ (Fig. 7) are also unexceptional, although the octahedron about the niobium is more distorted due to the small chelate bite of the 2,2'-bipyridyl ($\angle\text{N1}-\text{Nb1}-\text{N2} = 69.52(21)^\circ$).

Attempts to obtain a complex of NbOCl_3 with 1,4,7-trimethyl-1,4,7-triazacyclononane ($\text{Me}_3\text{-tacn}$) gave a mixture of products. Recrystallisation of the mixture from MeCN gave a few crystals identified as $[(\text{Me}_3\text{-tacn})\text{H}]_2[\text{NbOCl}_5]$. The anion



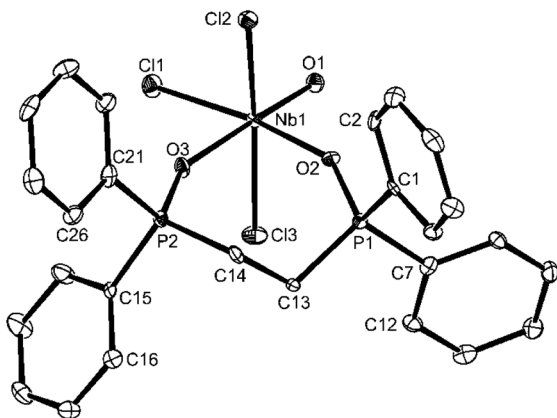


Fig. 5 The structure of $[\text{NbOCl}_3(\text{dppeO}_2)] \cdot n\text{MeCN}$ showing the atom labelling scheme. Displacement ellipsoids are drawn at the 50% probability level and H-atoms are omitted for clarity. The phenyl rings are numbered cyclically starting at the *ipso*-C atom. The solvate acetonitrile is also omitted. Selected bond lengths (Å) and angles (°): Nb1–O1 = 1.702(3), Nb1–O2 = 2.077(3), Nb1–O3 = 2.219(3), Nb1–Cl1 = 2.3602(12), Nb1–Cl3 = 2.4136(12), Nb1–Cl2 = 2.4210(13), O1–Nb1–O2 = 93.09(12), O2–Nb1–O3 = 82.31(10), O1–Nb1–Cl1 = 97.74(10), O3–Nb1–Cl1 = 86.86(8), O1–Nb1–Cl3 = 97.02(10), O2–Nb1–Cl3 = 86.17(8), O3–Nb1–Cl3 = 84.91(8), Cl1–Nb1–Cl3 = 92.43(4), O1–Nb1–Cl2 = 94.82(10), O2–Nb1–Cl2 = 86.11(8), O3–Nb1–Cl2 = 82.73(8), Cl1–Nb1–Cl2 = 93.00(4), Cl3–Nb1–Cl2 = 166.19(4).

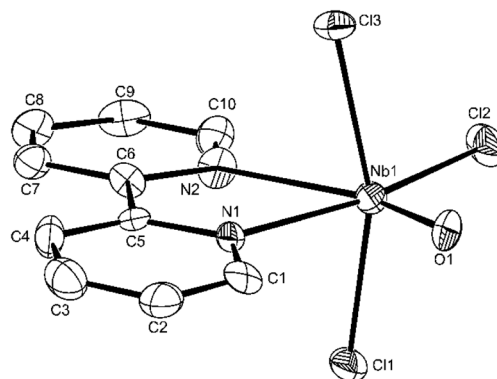


Fig. 7 The structure of the Nb1 centred molecule in $[\text{NbOCl}_3(2,2'\text{-bipy})]$ showing the atom labelling scheme. This molecule has no crystallographic symmetry whereas the Nb2 centred molecule has 2-fold symmetry. Displacement ellipsoids are drawn at the 50% probability level and H-atoms are omitted for clarity. Selected bond lengths (Å) and angles (°): Nb1–O1 = 1.694(6), Nb1–Cl1 = 2.363(2), Nb1–Cl2 = 2.356(2), Nb1–Cl3 = 2.372(2), Nb–N1 = 2.262(6), Nb1–N2 = 2.385(6), O1–Nb1–N1 = 89.3(3), O1–Nb1–Cl2 = 104.8(2), O1–Nb1–Cl1 = 98.0(2), O1–Nb1–Cl3 = 97.7(2), Cl2–Nb1–N2 = 96.41(15), N1–Nb1–N2 = 69.5(2), Cl1–Nb1–N1 = 84.50(16), Cl2–Nb1–Cl1 = 94.18(7), Cl3–Nb1–Cl2 = 92.76(7), Cl3–Nb1–N1 = 84.37(16), N2–Nb1–Cl1 = 81.08(15), Cl3–Nb1–N2 = 80.13(15).

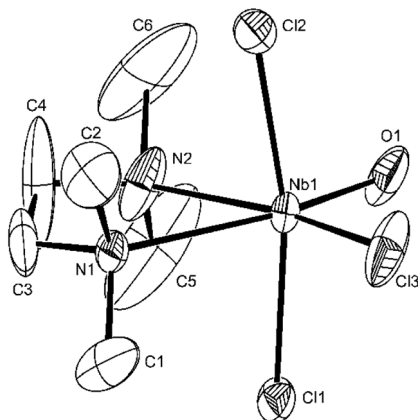


Fig. 6 The structure of $[\text{NbOCl}_3(\text{tmeda})]$ showing the atom labelling scheme. The carbon atoms associated with N2 show some disorder. Displacement ellipsoids are drawn at the 50% probability level and H-atoms are omitted for clarity. Selected bond lengths (Å) and angles (°): Nb1–O1 = 1.798(5), Nb1–N2 = 2.331(8), Nb1–N1 = 2.518(5), Nb1–Cl3 = 2.328(3), Nb1–Cl2 = 2.348(3), Nb1–Cl1 = 2.358(2), O1–Nb1–N2 = 92.5(3), O1–Nb1–Cl3 = 103.5(2), O1–Nb1–Cl2 = 94.3(3), N2–Nb1–Cl2 = 86.1(3), Cl3–Nb1–Cl2 = 91.21(16), O1–Nb1–Cl1 = 96.5(3), N2–Nb1–Cl1 = 87.6(3), Cl3–Nb1–Cl1 = 91.87(10), N2–Nb1–N1 = 74.1(2), Cl3–Nb1–N1 = 89.86(16), Cl2–Nb1–N1 = 84.00(15), Cl1–Nb1–N1 = 84.09(15), Cl2–Nb1–Cl1 = 167.70(10).

has been structurally characterised with a variety of cations, but often the niobium is on a high symmetry site which results in O/Cl disorder.¹⁷ In the present case the structure appears to be free of such disorder and the data are presented as ESI.†

Comparisons of NbF_5 , NbOF_3 and NbOCl_3 complexes

Comparison of the spectroscopic data in Table 1 for $[\text{NbF}_5(\text{OPR}_3)]$ and $[\text{NbOF}_3(\text{OPR}_3)_2]$ shows very significant differences due to replacement of two fluoride ligands by the oxo-group. The ^{19}F and ^{31}P chemical shifts are very different, with those of $[\text{NbF}_5(\text{OPR}_3)]$ at much higher frequency for each nucleus. Similar differences are apparent in the ^{19}F chemical shifts for the two series of N-donor complexes. The data demonstrate that the presence of the strong π -donating oxo-group significantly changes the electron density at the Nb(v) centre, making it much less electron poor, and hence a weaker Lewis acid. Within the NbOF_3 complexes there is also a large *trans* influence of the oxo-group which results in significantly longer bonds to the *trans* ligand than for those groups *trans* to fluorine. The $d(\text{P}=\text{O})$ show very small differences, although the relative *trans* influence is clear in the $\nu(\text{P}=\text{O})$ vibrations in the IR spectra. Comparing the structural and spectroscopic data on corresponding NbOF_3 and NbOCl_3 complexes reveals rather small differences. The $d(\text{Nb}=\text{O})$ in these and in literature examples of the oxide chloride complexes^{8,9,15,16} show they occur in a narrow range, $\sim 1.7\text{--}1.8$ Å, irrespective of the halide or neutral co-ligands present. Similarly, $d(\text{Nb}-\text{Cl})_{\text{trans L}}$ are relatively insensitive to the nature of L (the ligand types are too restricted to make a similar comparison for the fluoride).

The bond angles about the niobium centres also show significant deviations from those expected for a regular octahedral geometry. The factors determining the geometry adopted by ML_6 complexes of transition metals as a function of ligand types (σ -donor only, or σ and π donor), d^n count and ligand architecture have been discussed in several articles,¹⁸ and the fact that $[\text{MF}_6]^{n-}$ species are O_h and $[\text{M}(\text{CH}_3)_6]^{n-}$ ($n =$



0, 1, 2 *etc.*) are trigonal prisms has been rationalised in terms of electronic factors by MO calculations.¹⁹ The niobium oxide halide structures discussed in the present work (12e, d⁰ complexes) are based upon distorted octahedral geometries, as would be expected, given the presence of dominant σ and π donor ligands. As observed in many early transition metal complexes containing M=O bonds, the angles involving the latter, O=M-L and O=M-X are larger than X-M-X, X-M-L, or L-M-L, in effect the electron rich multiply bonded M=O unit occupies more space about the metal centre. Superimposed upon this are smaller effects arising from the steric demands of the X and L groups and constraints of neutral ligand geometries, such as chelate bites in the bidentates. In the *cis*-MOX₃L₂ unit the axial X-M-X group bends away from the M=O and towards the neutral co-ligands.^{2,3,5,8-10}

Comparing the IR data within the two series of NbOX₃ complexes shows $\nu(\text{Nb}=\text{O})$ lying in a range $\sim 920\text{--}970\text{ cm}^{-1}$, and the $\nu(\text{P}=\text{O})$ in corresponding phosphine oxide adducts also show little difference. Hence we conclude that the NbOX₃ core has the dominant structural and spectroscopic effects in these complexes.

The differences between NbOF₃ and NbOCl₃ as acceptors towards weaker donor ligands such as ethers or nitriles, where the latter forms complexes with thf, MeO(CH₂)₂OMe, MeCN, *etc.*,^{4,9,15} but attempts to isolate analogues with NbOF₃ result in intractable, ligand-free products (NbOF₃ polymer). This can be ascribed to the preference of the niobium centre to form fluoride bridges over weak Nb-L bonds, and is seen in other fluoride and oxide fluoride systems.¹

Finally, these niobium complexes can be compared with those of the 3d analogue, vanadium. VOF₃ forms similar phosphine oxide, diimine and diamine complexes to NbOF₃, but also complexes with ethers, thioethers and nitriles.² The differences are again readily rationalised by the niobium's preference for fluorine bridges; NbOF₃ is an inert, very strongly bridged polymer (above), whereas VOF₃ although (weakly) F-bridged in the solid,²⁰ easily vapourises as a monomer on heating and dissolves in most organic solvents. The complexes of VOCl₃ with neutral ligands are thermally and often photochemically unstable, and extremely readily hydrolysed and reduced (often spontaneously) to V(IV) or V(III) compounds,²¹ whereas the NbOCl₃ adducts remain pentavalent, unless specifically treated with reducing agents.

Conclusions

The O/F exchange reaction between complexes of the binary fluoride NbF₅ and a siloxane have been shown to produce complexes of the otherwise intractable oxide-fluoride, NbOF₃, in good yield. However, further O/F exchange to form derivatives of NbO₂F did not occur under similar conditions. Comparison of the spectroscopic properties of the NbF₅ and NbOF₃ complexes demonstrates the substantial effect on the metal centre of replacing two fluoride by the stronger π -donor oxido-group.

The HMDSO/MF_n route may well offer a synthetic pathway to oxide fluoride complexes of other high valent early metal complexes, *e.g.* those of Mo, W, Ti or Zr. TaOF₃ complexes are not formed under analogous reaction conditions; further studies are required to develop a suitable route to these.

Experimental

Infrared spectra were recorded as Nujol mulls between CsI plates using a Perkin-Elmer Spectrum 100 spectrometer over the range 4000–200 cm⁻¹. ¹H, ¹⁹F{¹H}, ³¹P{¹H} and ⁹³Nb NMR spectra were recorded using a Bruker DPX400 spectrometer and are referenced to the protio resonance of the solvent, external CFCl₃, 85% H₃PO₄, and [NEt₄][NbCl₆] in CD₃CN, respectively. Microanalyses were undertaken by Medac Ltd or London Metropolitan University. Solvents were dried prior to use: THF, Et₂O and MeOCH₂CH₂OMe by distillation from sodium benzophenone ketyl, MeCN and CH₂Cl₂ from CaH₂. OPMe₃ was sublimed *in vacuo*, OPPh₃, OAsPh₃, 2,2'-bipy, 1,10-phen were heated *in vacuo*, and tmeda distilled from BaO. All preparations were undertaken using standard Schlenk techniques under a N₂ atmosphere.

[NbF₅(OPPh₃)]: A solution of OPPh₃ (0.262 g, 1.0 mmol) in CH₂Cl₂ (20 mL) was added to finely powdered NbF₅ (0.188 g, 1.0 mmol), and vigorously stirred to give a clear solution. This was filtered to remove any residual solid and concentrated *in vacuo* to ~ 5 mL. On standing a white powdered separated, which was filtered off and dried *in vacuo*. Yield 0.40 g, 85%. Anal: required for C₁₈H₁₅F₅NbOP (466.2): C, 46.4; H, 3.2. Found: C, 46.9; H, 3.6%. ¹H NMR (CD₂Cl₂, 293 K): 7.1–7.6 (m). ¹⁹F{¹H} NMR (CD₂Cl₂, 293 K): +161.8 (s, [F]), +128.6 (s, [4F]); (210 K): +157.0 (s, [F]), +125.7 (s, [4F]). ³¹P{¹H} NMR (CD₂Cl₂, 293 K): 53.9 (s). ⁹³Nb NMR (CD₂Cl₂, 293 K): –1530 (br s). IR (Nujol/cm⁻¹): 1061 (vs) PO, 624 (sh), 608 (vs, br) NbF.

[NbF₅(OPMe₃)]: Made similarly to the OPPh₃ adduct. Yield 75%. Anal: required for C₃H₉F₅NbOP (280.0): C, 12.9; H, 3.2. Found: C, 13.2; H, 3.5%. ¹H NMR (CD₂Cl₂, 293 K): 1.9 (d, ²J_{PH} = 15 Hz). ¹⁹F{¹H} NMR (CD₂Cl₂, 293 K): 157.6 (s, [F]), 134.5 (s, [4F]). ³¹P{¹H} NMR (CD₂Cl₂, 293 K): +75.6 ⁹³Nb NMR (CD₂Cl₂, 293 K): –1530 (br, s). IR (Nujol/cm⁻¹): 1092 (vs) PO, 615 (vs, br), 582 (m) NbF.

[NbF₅(OAsPh₃)]: Prepared as for the OPPh₃ analogue except that the complex was prepared in ice-bath and solution stirred for 5 min. It was then concentrated *in vacuo* and the precipitated solid isolated immediately. If the solid is left in solution a yellow and then brown colour develops and *in situ* NMR data shows formation of Ph₃AsF₂, [NbF₆]⁻ and other unidentified impurities. The pure solid seems stable for some weeks in a freezer. Yield 55%. Anal: required for C₁₈H₁₅AsF₅NbO (510.1): C, 42.4; H, 3.0. Found: C, 42.4; H, 3.0%. ¹H NMR (CD₂Cl₂, 293 K): 7.2–7.6 (m). ¹⁹F{¹H} NMR (CD₂Cl₂, 293 K): +145.0 (s, [F]), +110.5 (s, [4F]). ⁹³Nb NMR (CD₂Cl₂, 293 K): –1511 (br, s). IR (Nujol/cm⁻¹): 845 (m) AsO, 620 (sh), 600 (vs, br) NbF.



[NbF₄(2,2'-bipy)₂][NbF₆]: NbF₅ (0.188 g, 1.0 mmol) was added to CH₂Cl₂ (20 mL) and vigorously stirred, whilst a solution of 2,2'-bipy (0.16 g, 1.0 mmol) in CH₂Cl₂ (10 mL) was added, resulting in rapid precipitation of a fine white powder. After 2 h the solid was isolated by filtration, rinsed with diethyl ether (5 mL) and dried *in vacuo*. Yield 0.30 g, 86%. Anal: required for C₂₀H₁₆F₁₀N₄Nb₂ (688.2): C, 34.9; H, 2.3; N, 8.1. Found: C, 34.7; H, 2.2, N, 8.1%. ¹H NMR (CD₂Cl₂, 293 K): 9.34 (d, [2H], *J* = 9 Hz), 8.63 (d, [2H], *J* = 9 Hz), 8.40 (m, [2H]), 7.78 (m, [2H]). ¹⁹F{¹H} NMR (CD₂Cl₂, 293 K): +139.7 (s, [4F]), +103.2 (10 lines, *J* = 335 Hz). IR (Nujol/cm⁻¹): 615 (vs), 603 (s), 585 (vs) NbF.

[NbF₄(1,10-phen)₂][NbF₆]: was made similarly in 89% yield. Anal: required for C₂₄H₁₆F₁₀N₄Nb₂ (736.2): C, 39.2; H, 2.2; N, 7.6. Found: C, 39.2; H, 2.3, N, 7.4%. ¹H NMR (CD₃CN, 293 K): 9.20 (d, [2H], *J* = 9 Hz), 8.96 (d, [2H], *J* = 9 Hz), 8.27 (m, [2H]), 8.17 (m, [2H]). ¹⁹F{¹H} NMR (CD₃CN, 293 K): +138.0 (s, [4F]), +103.4 (10 lines, *J* = 335 Hz). IR (Nujol/cm⁻¹): 608 (vs), 586 (vs), 565 (sh) NbF.

[NbOF₃(OPPh₃)₂]: NbF₅ (0.19 g, 1 mmol) and OPPh₃ (0.56 g, 2 mmol) were added to dry CH₂Cl₂ (25 mL) and the mixture stirred for 20 min. Hexamethyldisiloxane (0.16 g, 1 mmol) and MeCN (0.5 mL) were added and the mixture stirred overnight at room temperature. The solvents were removed *in vacuo* leaving a slightly sticky white powder which was stirred with dry diethyl ether (40 mL) when it became a fine white powder. This was filtered off, rinsed with diethyl ether (10 mL) and dried *in vacuo*. Yield 0.41 g, 57%. Refrigeration of the filtrate gave small crystals used for the X-ray data collection. Anal: required for C₃₆H₃₀F₃NbO₃P₂ (722.5): C, 59.9; H, 4.2. Found: C, 59.6; H, 4.3%. ¹H NMR (CD₂Cl₂, 293 K): 7.1–7.7 (m). ¹⁹F{¹H} NMR (CD₂Cl₂, 293 K): 49.5 (s, [F]), 37.8 (s, [2F]). ³¹P{¹H} NMR (CD₂Cl₂, 293 K): 45.0 (s, [P]), 36.0 (s, [P]). ⁹³Nb NMR (CD₂Cl₂, 293 K): not observed. IR (Nujol/cm⁻¹): 1155 (m), 1067 (s) PO, 941 (s) NbO, 602 (m), 579 (s) NbF.

[NbOF₃(OPMe₃)₂]: was made similarly Yield 50.5%. Crystals were obtained by refrigeration overnight of the filtrate from the synthesis solution. Anal: required for C₆H₁₈F₃NbO₃P₂·CH₂Cl₂ (435.0): C, 19.3; H, 4.6. Found: C, 18.7; H, 4.3%. ¹H NMR (CD₂Cl₂, 293 K): 1.60 (d, [H], ²*J*_{PH} = 13 Hz), 1.86 (d, [H], ²*J*_{PH} = 13 Hz). ¹⁹F{¹H} NMR (CD₂Cl₂, 293 K): 41.5 (s, [F]), 30.6 (s, [2F]). ³¹P{¹H} NMR (CD₂Cl₂, 293 K): 67.1 (s, [P]), 53.3 (s, [P]). ⁹³Nb NMR (CD₂Cl₂, 293 K): not observed. IR (Nujol/cm⁻¹): 1140 (m), 1087 (s) (PO), 958 (s), NbO, 614 (s), 555 (s) NbF.

[NbOF₃(2,2'-bipy)]: NbF₅ (0.19 g, 1 mmol) was dissolved in CH₂Cl₂ (200 mL) and dry 2,2'-bipy (0.16 g, 1 mmol) in CH₂Cl₂ (10 mL) was added with stirring. After 15 min. hexamethyldisiloxane (0.16 g, 1 mmol) and MeCN (0.5 mL) were added and the mixture stirred overnight at room temperature, producing a white precipitate. The mixture was concentrated to ~5 mL *in vacuo*, the white solid filtered off, rinsed with diethyl ether and dried *in vacuo*. Yield 0.27 g, 83%. Anal: required for C₁₀H₈F₃N₂NbO (322.1): C, 37.3; H, 2.5; N, 8.7. Found: C, 37.5; H, 2.4; N, 8.6%. ¹H NMR (CD₂Cl₂, 293 K): 9.28 (s, [H]), 9.17 (s, [H]), 8.54 (m, [H]), 8.36 (m, [H]), 8.32 (s, [2H]), 7.85 (s, [H]),

7.72 (s, [H]). ¹⁹F{¹H} NMR (CD₂Cl₂, 293 K): 49.0 (s, [F]), 42.8 (s, [2F]). IR (Nujol/cm⁻¹): 959 (s) NbO, 612 (vs), 579 (s) NbF.

[NbOF₃(1,10-phen)]: NbF₅ (0.19 g, 1 mmol) was dissolved in CH₂Cl₂ (200 mL) and dry 1,10-phen (0.18 g, 1 mmol) in CH₂Cl₂ (10 mL) added with stirring, producing some fine white precipitate. After 5 min hexamethyldisiloxane (0.16 g, 1 mmol) and MeCN (0.5 mL) were added and the mixture stirred for 48 h. at room temperature, producing a dense white precipitate. The precipitate was filtered off, rinsed with diethyl ether (10 mL) and dried *in vacuo*. Yield 0.30 g, 86%. Anal: required for C₁₂H₈F₃N₂NbO (346.1): C, 41.6; H, 2.3; N, 8.1. Found: C, 41.4; H, 2.3; N, 7.9%. ¹H NMR (CD₂Cl₂, 293 K): 9.36 (s, [H]), 9.28 (s, [H]), 8.77 (m, [H]), 8.56 (m, [H]), 8.19 (s, [H]), 8.13 (s, [H]), 8.02 (s, [H]), 7.90 (s, [H]). ¹⁹F{¹H} NMR (CD₂Cl₂, 293 K): insufficiently soluble. IR (Nujol/cm⁻¹): 970 (s) NbO, 610 (sh), 594 (s), 583 (s) NbF.

[NbOF₃(dppmO₂)]: NbF₅ (0.19 g, 1 mmol) and dppmO₂ (0.41 g, 1 mmol) were added to dry CH₂Cl₂ (25 mL) and the mixture stirred for 20 min. Hexamethyldisiloxane (0.16 g, 1 mmol) and MeCN (0.5 mL) were added and the mixture stirred overnight at room temperature. The solvents were removed *in vacuo* leaving a slightly sticky cream powder which was extracted with CH₂Cl₂ (20 mL), filtered to remove some undissolved solid, and concentrated to ~5 mL. Dry diethyl ether (20 mL) was added slowly and the cream precipitate filtered off and dried *in vacuo*. Yield 0.34 g, 45%. Refrigeration of the filtrate for 5 d. gave crystals suitable for the X-ray data collection. Anal: required for C₂₅H₂₂F₃NbO₃P₂ (582.3): C, 51.6; H, 3.8. Found: C, 51.5; H, 3.9%. ¹H NMR (CD₂Cl₂, 293 K): 7.82–7.15 (m, [10H]), 3.70 (m, [H], *J* = 13 Hz). ¹⁹F{¹H} NMR (CD₂Cl₂, 293 K): 55.7 (s, [F]), 36.4 (s, [2F]). ³¹P{¹H} NMR (CD₂Cl₂, 293 K): 46.4(d, [P], ²*J*_{pp} = 17 Hz), 36.8 (s, [P], ²*J*_{pp} = 17 Hz). IR (Nujol/cm⁻¹): 1156 (s), 1088 (s) PO, 944 (s) NbO, 608 (vs), 582 (s) NbF.

[NbOF₃(dmsO)₂]: NbF₅ (0.19 g, 1 mmol) was added to dry CH₂Cl₂ (25 mL), followed by dry dmsO (0.5 mL) and the mixture stirred for 20 min. producing a clear colourless solution. Hexamethyldisiloxane (0.16 g, 1 mmol) and MeCN (0.5 mL) were added and the mixture stirred for 6 h at room temperature, during which a fine microcrystalline solid was deposited. The solid was filtered off, rinsed by diethyl ether (5 mL) and dried *in vacuo*. Yield 0.25 g, 78%. Anal: required for C₄H₁₂F₃NbO₃S₂ (322.2): C, 14.9; H, 3.8. Found: C, 15.1; H, 3.9%. ¹H NMR (CD₂Cl₂, 293 K): 2.65 (br); (253 K): 2.59 ([6H]), 2.55 ([6H]). ¹⁹F{¹H} NMR (CD₂Cl₂, 293 K): 50.4 (s, [F]), 38.0 (s, [2F]). IR (Nujol/cm⁻¹): 1039 (s), 1005 (s) Me₂SO, 920 (s) NbO, 590 (s), 564 (s) NbF.

[NbOF₃(tmeda)]: NbF₅ (0.19 g, 1 mmol) was added to dry CH₂Cl₂ (200 mL), followed by dry tmeda (0.12 g, 1 mmol) and the mixture stirred for 20 min. producing a cloudy suspension. Hexamethyldisiloxane (0.16 g, 1 mmol) and MeCN (0.5 mL) were added and the mixture stirred overnight at room temperature, during which a fine white powder was deposited. The solid was filtered off, rinsed by diethyl ether (5 mL) and dried *in vacuo*. Yield 0.24 g, 85%. Anal: required for C₆H₁₆F₃N₂NbO·CH₂Cl₂ (367.0): C, 21.9; H, 4.9; N, 7.6. Found:



C, 21.4; H, 5.5; N, 7.9%. Insoluble in non-donor solvents. IR (Nujol/cm⁻¹): 920 (s) NbO, 587 (s) 557 (s) NbF.

[NbOCl₃(2,2'-bipy)]: NbCl₅ (0.067 g, 0.25 mmol) was dissolved into acetonitrile (4 mL) to give a bright yellow-green solution. Hexamethyldisiloxane (0.040 g, 0.25 mmol) was added and the mixture was stirred for 10 min. during which time the solution turned very pale. 2,2'-Bipy (0.039 g, 0.25 mmol) in acetonitrile (4 mL) was added slowly with stirring. After 30 min. the solution was concentrated *in vacuo* and the white precipitate filtered off, and dried *in vacuo*. Yield 0.048 g, 52%. Crystals of [NbOCl₃(2,2'-bipy)] were grown from acetonitrile solution in the freezer. Anal: required for C₁₀H₈Cl₃N₂NbO (371.4): C, 32.3; H, 2.2; N, 7.5. Found: C, 32.3; H, 2.1; N, 7.7%. ¹H NMR (CD₂Cl₂, 295 K): 8.98 (s, [H]), 8.91 (s, [H]), 8.31 (br m, [4H]), 7.79 (s, [H]), 7.73 (s, [H]). IR (Nujol/cm⁻¹): 943 (s) NbO, 349 (s), 338 (s) NbCl.

[NbOCl₃(1,10-phen)]: The white compound was made in an analogous way to [NbOCl₃(2,2'-bipy)]. Yield 61%. Anal: required for C₁₂H₈Cl₃N₂NbO (395.4): C, 36.4; H, 2.0; N, 7.1. Found: C, 36.3; H, 2.0; N, 7.1%. ¹H NMR (CD₂Cl₂, 295 K): 9.86 (s, [H]), 9.75 (s, [H]), 8.88 (m, [H]), 8.74 (m, [H]), 8.17 (s, [2H]), 8.08 (s, [2H]). IR (Nujol/cm⁻¹): 944 (s) NbO, 338 (vbr, s) NbCl.

[NbOCl₃(tmeda)]: NbCl₅ (0.270 g, 1.0 mmol) was dissolved into acetonitrile (10 mL) and hexamethyldisiloxane (0.244 g, 1.5 mmol) was added. After 10 min. tmeda (0.14 g, 1.2 mmol) in dichloromethane (4 mL) was added slowly to the reaction mixture with stirring. After 2 h the mixture was concentrated *in vacuo* and the resulting precipitate was filtered off and dried *in vacuo*. Yield 0.055 g, 17%. Single crystals of [NbOCl₃(tmeda)] were grown from the filtrate in the freezer. Anal: required for C₆H₁₆Cl₃N₂NbO (331.4): C, 21.7; H, 4.9; N, 8.5. Found: C, 21.6; H, 4.8; N, 8.4%. ¹H NMR (CD₂Cl₂, 295 K): insoluble. IR (Nujol/cm⁻¹): 945 (s) NbO, 341 (s) 320 (sh) NbCl.

[NbOCl₃(OPPh₃)₂]: NbCl₅ (0.270 g, 1.0 mmol) was dissolved in acetonitrile (5 mL) whilst stirring and hexamethyldisiloxane (0.162 g, 1.0 mmol) was added. After 10 min. OPPh₃ (0.556 g, 2 mmol) was added producing a milky white mixture. The reaction was left to stir for 2 h and the white solid filtered off and dried *in vacuo*. Yield: 0.450 g, 58%. Anal: required for C₃₆H₃₀O₃Cl₃NbP₂ (771.8): C, 56.0; H, 3.9. Found: C, 55.7; H, 3.6%. ¹H NMR (CD₂Cl₂, 295 K): 7.7–7.2 (m). ³¹P{¹H} NMR (CDCl₃, 298 K): 50.0 (s, [P]), 38.8 (s, [P]). IR (Nujol/cm⁻¹): 1159 (s), 1074(s) PO, 936 (s) NbO, 325(s), 294(m) NbCl.

[NbOCl₃(dppeO₂)]: NbCl₅ (0.068 g, 0.25 mmol) was dissolved in acetonitrile (5 mL) and hexamethyldisiloxane (0.062 g, 0.38 mmol) was added. The mixture was left to stir for 15 min. and then dppeO₂ (0.108 g, 0.25 mmol) was added and the reaction was left to stir overnight. The precipitate was filtered off, rinsed with small amount of CH₂Cl₂ and dried *in vacuo*. Yield 0.102 g, 63%. Crystals of [NbOCl₃(dppeO₂)] were grown from CH₂Cl₂ solution in the freezer. Anal: required for C₂₆H₂₄Cl₃NbO₃P₂ (645.6): C, 48.4; H, 3.8. Found: C, 48.6; H, 4.0%. ¹H NMR (CD₂Cl₂, 295 K): 7.89–7.48 (m [10H]), 2.84 (m, [H]), 2.62 (m, [H]). ³¹P{¹H} NMR (CDCl₃, 298 K): 56.7 (s), 44.9 (s). IR (Nujol/cm⁻¹): 1172 (s), 1066 (s) PO, 943 (s) NbO, 320 (s), 293 (w) NbCl.

[NbOCl₃(dppmO₂)]: was made similarly to [NbOCl₃(dppeO₂)]. Yield 67%. Crystals of [NbOCl₃(dppmO₂)] were grown from a saturated dichloromethane solution in the freezer. Anal: required for C₂₅H₂₂Cl₃NbO₃P₂ (631.6): C, 46.7; H, 3.5. Found: C, 46.8; H, 3.9%. ¹H NMR (CD₂Cl₂, 295 K): 7.75–7.35 (m, [10H]), 3.80 (t, [H], ²J_{PH} = 15 Hz). ³¹P{¹H} NMR (CH₂Cl₂-CDCl₃, 298 K): 48.5 (d, ²J_{PP} = 19 Hz) 36.8 (d, ²J_{PP} = 19 Hz). IR (Nujol/cm⁻¹): 1157 (s), 1095 (s) PO, 928 (s) NbO, 327 (s), 294 (m) NbCl.

[TaF₅(OPPh₃)]: A solution of OPPh₃ (0.26 g, 1.0 mmol) in CH₂Cl₂ (20 mL) was added to finely powdered TaF₅ (0.28 g, 1.0 mmol), and vigorously stirred to give a clear solution. This was filtered to remove any residual solid and concentrated *in vacuo* to ~2 mL. On standing a white powder separated, which was filtered off and dried *in vacuo*. Yield 0.45 g, 81%. Anal: required for C₁₈H₁₅F₅OPTa (554.2): C, 39.0; H, 2.7. Found: C, 38.5; H, 2.9%. ¹H NMR (CD₂Cl₂, 293 K): 7.2–7.6 (m). ¹⁹F{¹H} NMR (CD₂Cl₂, 293 K): 84.2 (s, [F]), 54.7 (s, [4F]); (210 K): 81.8 (s, [F]), 56.3 (s, [4F]). ³¹P{¹H} NMR (CD₂Cl₂, 293 K): 53.2(s). IR (Nujol/cm⁻¹): 1078 (vs) PO, 617 (sh), 592 (vs, br) TaF.

[TaF₅(OAsPh₃)]: was made similarly, from OAsPh₃ (0.32 g, 1.0 mmol) and TaF₅ (0.28 g, 1.0 mmol), except that the reaction was worked up and the solid isolated after 20 min. Yield 0.50 g, 85%. Anal: required for C₁₈H₁₅AsF₅OTa (598.2): C, 36.2; H, 2.5. Found: C, 37.3; H 2.6%. ¹H NMR (CD₂Cl₂, 293 K): 7.2–7.6 (m). ¹⁹F{¹H} NMR (CD₂Cl₂, 293 K): 62.5 (s, [F]), 48.6 (s, [4F]), weak resonances at 38.6 ([TaF₆]⁻) and -89.4 (Ph₃AsF₂). IR (Nujol/cm⁻¹): 845 (s) AsO, 620 (sh), 581 (vs, br) TaF.

[TaF₅(OPMe₃)]: A solution of OPMe₃ (0.092 g, 1.0 mmol) in CH₂Cl₂ (10 mL) was added to finely powdered TaF₅ (0.276 g, 1.0 mmol), and vigorously stirred to give a clear solution. This was filtered to remove any residual solid and concentrated *in vacuo* to ~5 mL. A white powder separated, which was filtered off and dried *in vacuo*. Yield 0.25 g, 65%. Anal: required for C₃H₉F₅OPTa (368.0): C, 9.8; H, 2.5. Found: C, 10.2; H, 2.3%. ¹H NMR (CD₂Cl₂, 293 K): 1.9 (d, ²J_{PH} = 15 Hz). ¹⁹F{¹H} NMR (CD₂Cl₂, 293 K): 82.5 (s, [F]), 55.9 (s, [4F]). ³¹P{¹H} NMR (CD₂Cl₂, 293 K): 76.9 (s). IR (Nujol/cm⁻¹): 1092 (vs) PO, 601 (sh), 583 (vs, br) TaF.

[TaF₄(2,2'-bipy)₂][TaF₆]: TaF₅ (0.28 g, 1.0 mmol) was added to CH₂Cl₂ (50 mL) and vigorously stirred, whilst a solution of 2,2'-bipy (0.16 g, 1.0 mmol) in CH₂Cl₂ (10 mL) was added, resulting in rapid precipitation of a fine white powder. After 24 h the solid was isolated by filtration, rinsed with diethyl ether (5 mL) and dried *in vacuo*. Yield 0.35 g, 86%. Anal: required for C₂₀H₁₆F₁₀N₄Ta₂ (864.2): C, 27.8; H, 1.9; N, 6.5. Found: C, 27.9; H, 1.9; N, 6.4%. ¹H NMR (CD₂Cl₂, 293 K): 9.34 (d, [2H], J = 9 Hz), 8.50 (d, [2H], J = 8 Hz), 8.37 (m, [2H]), 7.81 (m, [2H]). ¹⁹F{¹H} NMR (CD₂Cl₂, 293 K): 68.1 (s, [4F]), 38.0 (s, [6F]). IR (Nujol/cm⁻¹): 605 (sh), 581 (vs) TaF.

[TaF₄(1,10-phen)₂][TaF₆]: was made similarly. Yield 83%. Anal: required for C₂₄H₁₆F₁₀N₄Ta₂ (912.3): C, 31.6; H, 1.8; N, 6.1. Found: C, 31.5; H, 1.8; N, 6.0%. ¹H NMR (CD₂Cl₂, 293 K): 9.15 (s, [2H]), 8.63 (d, [2H], J = 10 Hz), 8.09 (s, [2H]), 7.92 (m, [2H]). ¹⁹F{¹H} NMR (CD₂Cl₂, 293 K): 66.1 (s, [4F]), 37.9 (s, [6F]). IR (Nujol/cm⁻¹): 605 (sh), 576 (vs) TaF.



Table 2 X-ray data^a

Compound	[NbOF ₃ (OPPh ₃) ₂]	[NbOF ₃ (OPMe ₃) ₂].0.33CH ₂ Cl ₂	[NbOF ₃ (dppmO ₂)]	[NbOCl ₃ (dppmO ₂).0.3MeCN
Formula	C ₃₆ H ₃₀ F ₃ NbO ₃ P ₂	C ₆ H ₁₈ F ₃ NbO ₃ P ₂ .0.33CH ₂ Cl ₂	C ₂₅ H ₂₂ F ₃ NbO ₃ P ₂	C ₂₅ H ₂₂ Cl ₃ NbO ₃ P ₂ .0.3CH ₃ CN
<i>M</i>	722.45	378.36	582.28	643.94
Crystal system	Orthorhombic	Triclinic	Monoclinic	Monoclinic
Space group (no.)	<i>Fdd2</i> (no. 43)	<i>P1</i> (no. 2)	<i>P2₁/n</i> (no. 14)	<i>P2₁/n</i> (no. 14)
<i>a</i> /Å	18.762(9)	7.8890(15)	13.154(8)	10.694(2)
<i>b</i> /Å	33.289(14)	14.584(3)	10.967(6)	15.640(4)
<i>c</i> /Å	10.152(5)	20.046(4)	17.248(10)	17.181(4)
α /°	90	102.497(4)	90	90
β /°	90	99.803(4)	97.173(19)	105.721(6)
γ /°	90	97.324(2)	90	90
<i>U</i> /Å ³	6340(5)	2186.3(7)	2469(3)	2766.0(13)
<i>Z</i>	8	6	4	4
μ (Mo-K α)/mm ⁻¹	0.534	1.191	0.665	0.867
<i>F</i> (000)	2944	1140	1176	1298
Total number reflns	7136	22 109	15 969	11 311
<i>R</i> _{int}	0.0849	0.0250	0.0915	0.0386
Unique reflns	3000	9978	4794	5288
No. of params, restraints	204, 20	556, 15	307, 0	320, 2
<i>R</i> ₁ , <i>wR</i> ₂ [<i>I</i> > 2 σ (<i>I</i>)] ^b	0.0719, 0.1062	0.0359, 0.0847	0.0770, 0.1725	0.0514, 0.0946
<i>R</i> ₁ , <i>wR</i> ₂ (all data)	0.0888, 0.1148	0.0430, 0.0880	0.0982, 0.1854	0.0742, 0.1045
Compound	[NbOCl ₃ (dppeO ₂)]·0.5MeCN	[NbOCl ₃ (2,2'-bipy)]	[NbOCl ₃ (tmeda)]	
Formula	C ₂₆ H ₂₄ Cl ₃ NbO ₃ P ₂ .0.5CH ₃ CN	C ₁₀ H ₈ Cl ₃ N ₂ NbO	C ₆ H ₁₆ Cl ₃ N ₂ NbO	
<i>M</i>	666.18	371.44	331.47	
Crystal system	Monoclinic	Orthorhombic	Orthorhombic	
Space group (no.)	<i>P2₁/n</i> (no. 14)	<i>Fdd2</i> (no. 43)	<i>Pna2₁</i> (no. 33)	
<i>a</i> /Å	10.752(2)	12.4975(4)	14.352(7)	
<i>b</i> /Å	14.367(3)	21.6322(8)	7.368(4)	
<i>c</i> /Å	18.048(4)	29.090(2)	11.781(6)	
α /°	90	90	90	
β /°	92.519(10)	90	90	
γ /°	90	90	90	
<i>U</i> /Å ³	2785.1(10)	7864.3(6)	1245.8(11)	
<i>Z</i>	4	24	4	
μ (Mo-K α)/mm ⁻¹	0.864	1.512	1.578	
<i>F</i> (000)	1348	4368	664	
Total number reflns	14 141	5418	3500	
<i>R</i> _{int}	0.0555	0.0243	0.0196	
Unique reflns	5451	2991	2135	
No. of params, restraints	338, 2	240, 16	119, 2	
<i>R</i> ₁ , <i>wR</i> ₂ [<i>I</i> > 2 σ (<i>I</i>)] ^b	0.0591, 0.0921	0.0469, 0.1169	0.0449, 0.1102	
<i>R</i> ₁ , <i>wR</i> ₂ (all data)	0.0721, 0.0968	0.0506, 0.1204	0.0521, 0.1162	

^a Common items: *T* = 100 K; wavelength (Mo-K α) = 0.71073 Å; θ (max) = 27.5°. ^b $R_1 = \sum ||F_o| - |F_c|| / \sum |F_o|$; $wR_2 = [\sum w(F_o^2 - F_c^2)^2 / \sum wF_o^4]^{1/2}$.

X-Ray experimental

Details of the crystallographic data collection and refinement parameters are given in Table 2. Crystals suitable for single crystal X-ray analysis were obtained as described above. Data collections used a Rigaku AFC12 goniometer equipped with an enhanced sensitivity (HG) Saturn724+ detector mounted at the window of an FR-E+ SuperBright molybdenum ($\lambda = 0.71073$ Å) rotating anode generator with VHF Varimax optics (100 μ m focus) with the crystal held at 100 K (N₂ cryostream). Structure solution and refinement were straightforward,^{22,23} except as detailed below, with H atoms bonded to C being placed in calculated positions using the default C–H distance. Several cases of O/X disorder have been discussed in the text. Three of the carbon atoms in [NbOCl₃(tmeda)], C4, C5 and C6 were elongated, suggesting some disorder, but attempts to split these over two positions were unsuccessful. For [NbOCl₃(2,2'-bipy)] Nb2 was initially placed on the two-fold axis but showed

a very elongated ellipsoid with two large Q peaks close to Nb2. A subsequent model displaced Nb2 by a few tenths of an Å from the axis and this gave a better fit to the data, *R*₁ reduced from ~0.08 to ~0.05.

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References

- 1 S. L. Benjamin, W. Levason and G. Reid, *Chem. Soc. Rev.*, 2013, **42**, 1460.



- 2 (a) J. Sala-Pala and J. E. Guerschais, *J. Mol. Struct.*, 1974, **20**, 169; (b) M. F. Davis, W. Levason, J. Paterson, G. Reid and M. Webster, *Eur. J. Inorg. Chem.*, 2008, 802; (c) M. D. Hoops and B. S. Ault, *J. Mol. Struct.*, 2002, **616**, 91.
- 3 (a) A. J. Edwards, D. R. Slim, J. Sala-Pala and J. E. Guerschais, *J. Chem. Soc., Dalton Trans.*, 1977, 984; (b) M. F. Davis, M. Jura, A. Leung, W. Levason, B. Littlefield, G. Reid and M. Webster, *Dalton Trans.*, 2008, 6265; (c) P. DeBurgomaster and J. Zubieta, *Acta Crystallogr., Sect. E: Struct. Rep. Online*, 2010, **66**, m1303.
- 4 (a) F. Marchetti and G. Pampaloni, *Chem. Commun.*, 2012, **48**, 635; (b) R. Bini, C. Chiappe, F. Marchetti, G. Pampaloni and S. Zacchini, *Inorg. Chem.*, 2010, **49**, 339; (c) F. Marchetti, G. Pampaloni and S. Zacchini, *Inorg. Chem.*, 2008, **47**, 365; (d) F. Marchetti, G. Pampaloni and S. Zacchini, *J. Fluorine Chem.*, 2010, **131**, 21; (e) F. Marchetti, G. Pampaloni and S. Zacchini, *Dalton Trans.*, 2009, 8096; (f) F. Marchetti, G. Pampaloni and S. Zacchini, *Dalton Trans.*, 2009, 6759; (g) M. Bortoluzzi, F. Marchetti, G. Pampaloni, M. Puchino and S. Zacchini, *Dalton Trans.*, 2013, **42**, 13054.
- 5 (a) M. Jura, W. Levason, R. Ratnani, G. Reid and M. Webster, *Dalton Trans.*, 2010, **39**, 883; (b) S. L. Benjamin, A. Hyslop, W. Levason and G. Reid, *J. Fluorine Chem.*, 2012, **137**, 77.
- 6 J. Köhler, A. Simon, L. van Wüllen, S. Cordier, T. Roisnel, M. Poulain and M. Somer, *Z. Anorg. Allg. Chem.*, 2002, **628**, 2683.
- 7 (a) T. Funaioli, F. Marchetti, G. Pampaloni and S. Zacchini, *Dalton Trans.*, 2013, **42**, 14168; (b) J. Sala-Pala, J. Y. Calves and J. Guerschais, *J. Inorg. Nucl. Chem.*, 1975, **37**, 1296.
- 8 L. G. Hubert-Pfalzgraf, M. Postel and J. G. Reiss, in *Comprehensive Coordination Chemistry*, ed. G. Wilkinson, R. D. Gillard and J. A. McCleverty, Pergamon, Oxford, 1987, vol. 3, p. 585.
- 9 (a) W. A. Herrmann, W. R. Thiel and E. Herdtweck, *Chem. Ber.*, 1990, **123**, 271; (b) V. C. Gibson and T. P. Kee, *J. Chem. Soc., Dalton Trans.*, 1993, 1657; (c) V. C. Gibson, T. P. Kee and A. Shaw, *Polyhedron*, 1988, **7**, 2217; (d) V. C. Gibson, T. P. McKee, R. M. Sorrell, A. P. Bashall and M. McPartlin, *Polyhedron*, 1988, **7**, 2221; (e) F. Marchetti, G. Pampaloni and S. Zacchini, *Chem. Commun.*, 2008, 3651.
- 10 (a) K. Dreisch, C. Andersson and C. Stalhandske, *Polyhedron*, 1991, **10**, 2417; (b) M. F. Davis, W. Levason, R. Ratnani, G. Reid, T. Rose and M. Webster, *Eur. J. Inorg. Chem.*, 2007, 306; (c) M. F. Davis, W. Levason, M. E. Light, R. Ratnani, G. Reid, K. Saraswat and M. Webster, *Eur. J. Inorg. Chem.*, 2007, 1903.
- 11 Yu. A. Buslaev, E. G. Ilyin, M. E. Ignatov, I. S. Butorina and T. A. Mastryukova, *J. Fluorine Chem.*, 1978, **12**, 381.
- 12 (a) C. Djordjevic and V. Katovic, *J. Chem. Soc. A*, 1970, 3382; (b) M. E. Ignatov, D. B. Grebshekov and E. G. Il'in, *Russ. J. Inorg. Chem.*, 1983, **28**, 617.
- 13 S. L. Benjamin, W. Levason, D. Pugh, G. Reid and W. Zhang, *Dalton Trans.*, 2012, **41**, 12548.
- 14 M. Stroebel and H.-J. Meyer, *Z. Anorg. Allg. Chem.*, 2002, **628**, 488.
- 15 C. Chavant, J. C. Daran, Y. Jeannin, G. Constant and R. Morancho, *Acta Crystallogr., Sect. B: Struct. Crystallogr. Cryst. Chem.*, 1975, **31**, 1828.
- 16 V. S. Sergienko, M. A. Porai-Koshits, A. A. Konovalova and V. V. Kovalev, *Koord. Khim.*, 1984, **10**, 1116.
- 17 (a) M. Weishaupt and J. Straehle, *Z. Anorg. Allg. Chem.*, 1977, **429**, 261; (b) J. Poitras and A. L. Beauchamp, *Can. J. Chem.*, 1994, **72**, 1675; (c) U. Mueller and I. Lorenz, *Z. Anorg. Allg. Chem.*, 1980, **463**, 110.
- 18 (a) D. L. Kepert, *Prog. Inorg. Chem.*, 1977, **23**, 1; (b) R. Hoffmann, J. M. Howell and A. R. Rossi, *J. Am. Chem. Soc.*, 1976, **98**, 2484.
- 19 (a) S. El-Kurdi and K. Seppelt, *Chem.-Eur. J.*, 2011, **17**, 3956; (b) K. Seppelt, *Acc. Chem. Res.*, 2003, **36**, 147.
- 20 J. Supel, U. Abram, A. Hagenbach and K. Seppelt, *Inorg. Chem.*, 2007, **46**, 5591.
- 21 C. D. Beard, R. J. Barrie, J. Evans, W. Levason, G. Reid and M. D. Spicer, *Eur. J. Inorg. Chem.*, 2006, 4391.
- 22 G. M. Sheldrick, *SHELXL-97, Program for refinement of crystal structures*, University of Göttingen, Germany, 1997.
- 23 G. M. Sheldrick, *SHELXS-97, Program for solution of crystal structures*, University of Göttingen, Germany, 1997.
- 24 S. M. Corcoran, W. Levason, R. Patel and G. Reid, *Inorg. Chim. Acta*, 2005, **358**, 1263.

