Bulk and Surface Chemistry of the Niobium MAX and MXene Phases from Multinuclear Solid-State NMR Spectroscopy

Kent J. Griffith,¹,₂,† Michael A. Hope,¹,† Philip J. Reeves,¹ Mark Anayee,³ Yury Gogotsi,³ Clare P. Grey¹

¹Department of Chemistry, University of Cambridge, Cambridge, CB2 1EW, United Kingdom
²Department of Chemistry and Department of Materials Science and Engineering, Northwestern University, Evanston, IL 60208, United States
³A. J. Drexel Nanomaterials Institute, and Department of Materials Science and Engineering, Drexel University, Philadelphia, PA 19104, United States
†Authors contributed equally

Abstract

MXenes, derived from layered MAX phases, are a class of two-dimensional materials with emerging applications in energy storage, electronics, catalysis, and other fields due to their high surface areas, metallic conductivity, biocompatibility and attractive optoelectronic properties. MXene properties are heavily influenced by their surface chemistry, but a detailed understanding of the surface functionalization is still lacking. Solid-state nuclear magnetic resonance (NMR) spectroscopy is sensitive to the interfacial chemistry, the phase purity including the presence of amorphous/nanocrystalline phases, and the electronic properties of the MXene and MAX phases. In this work, we systematically study the chemistry of Nb MAX and MXene phases, Nb₂CTₓ and Nb₄C₃Tₓ, with their unique electronic and mechanical properties, using solid-state NMR spectroscopy and examine a variety of nuclei (¹H, ¹³C, ¹⁹F, ²⁷Al and ⁹³Nb) with a range of one- and two-dimensional correlation, wideline, high-sensitivity, high-resolution, and/or relaxation-filtered experiments. Hydroxide and fluoride terminations are identified, found to be intimately mixed, and their chemical shifts are compared with other MXenes. This multinuclear NMR study demonstrates that diffraction alone is insufficient to characterize the phase composition of MAX and MXene samples as numerous amorphous or
nanocrystalline phases are identified including NbC, AlO$_6$ species, aluminum nitride or oxycarbide, AlF$_3$·$_n$H$_2$O, Nb metal, and unreacted MAX phase. To the best of our knowledge, this is the first study to examine the transition-metal resonances directly in MXene samples, and the first $^{93}$Nb NMR of any MAX phase. The insights from this work are employed to enable the previously elusive assignment of the complex overlapping $^{47/49}$Ti NMR spectrum of Ti$_3$AlC$_2$. The results and methodology presented here provide fundamental insights on MAX and MXene phases and can be used to obtain a more complete picture of MAX and MXene chemistry, to prepare realistic structure models for computational screening, and to guide the analysis of property measurements.
Introduction

MAX phases (M = early transition metal; A = Al, Si, Ga; X = C, N) are a large class of 3D layered ternary compounds with the stoichiometry $M_{n+1}AX_n$ ($1 \leq n \leq 3$).\textsuperscript{1–4} MXenes are a similarly diverse class of 2D compounds derived from MAX phases via etching of the A-site atoms.\textsuperscript{5} It is well-established that MXenes are surface-terminated, and thus better represented by the formula $M_{n+1}X_nT_\chi$ ($T = \text{termination}$), however the nature of the surface composition, coordination, and spatial arrangements are exceptionally challenging to ascertain (Figure 1). Both material families have extremely diverse applications: MAX phases are used for industrial components such as heating elements and gas burner nozzles with high temperature applications\textsuperscript{1,3,6} and MXenes are being tested as functional materials for applications in energy storage,\textsuperscript{7,8} hydrogen\textsuperscript{9,10} and oxygen\textsuperscript{11,12} evolution catalysis, cancer therapeutics,\textsuperscript{13} and electromagnetic interference shielding\textsuperscript{14,15}. The electronic and functional properties of MXenes depend strongly on the surface terminations,\textsuperscript{16–18} so a deeper understanding of the surface chemistry is required to optimize the performance in these applications.

Figure 1 – Crystal structures of the niobium MAX and surface-terminated MXene compounds. In (a) Nb$_2$AlC and (b) Nb$_4$AlC$_3$, the crystallographic sites are labeled and the unit cells are outlined. Table 1 describes the local coordination around each atom. The corresponding MXenes (c) Nb$_2$CT$_\chi$ and (d) Nb$_4$C$_3$T$_\chi$, showing –F, –O and –OH terminations; two layers and interlayer water are shown for Nb$_2$CT$_\chi$. 
As the first reported MXene, Ti$_3$C$_2$T$_x$ has been the most thoroughly studied member of this family, while many other MXenes have been, and continue to be, synthesized and applied to diverse functions. In this work, on the other hand, we focus on the less studied 4$d$ transition metal-based niobium MAX and MXene phases including Nb$_4$AlC$_3$, Nb$_4$C$_3$T$_x$, Nb$_2$AlC, and Nb$_2$CT$_x$, and Nb$_2$SnC. While Nb$_2$AlC$^{19}$ and Nb$_2$SnC$^{20}$ were reported in the 1960s, it was not until the 2000s that Nb$_4$AlC$_3$ emerged$^{21}$ via a synthesis strategy borrowed from the synthesis of the Ta MAX series. The syntheses of Nb$_2$CT$_x$$^{22}$ and Nb$_4$C$_3$T$_x$$^{23}$ MXenes were then reported in 2013 and 2014, respectively, by selective etching of Al from Nb$_2$AlC and Nb$_4$AlC$_3$, following the same methodology as for Ti$_3$C$_2$T$_x$. Neither the intermediate compound Nb$_3$AlC$_2$ nor its MXene derivative have been reported; density functional theory (DFT) calculations suggest that this 312 MAX phase is dynamically unstable.$^{24}$ The Nb MAX and MXene phases have various interesting properties and potential applications including in biomedical$^{13,25}$ and optical$^{26}$ applications. Nb$_2$CT$_x$$^{22}$ and Nb$_4$C$_3$T$_x$$^{27}$ have attracted recent interest as lithium-ion battery anodes. Nb$_4$C$_3$T$_x$ is one of the most conductive and strongest MXene phases,$^{23}$ which makes it promising for field-effect transistors and mechanical applications.$^{28}$ Nb$_2$SnC$^{29}$ and Nb$_2$AlC$^{30}$ are superconducting up to 7.8 K and 0.440 K, respectively. Superconductivity was recently observed in Nb$_2$CT$_x$ at 4.5 to 7.1 K, the temperature depending on the surface termination.$^{18}$

The structures of the Nb MAX and MXene phases are shown in Figure 1, with the first-shell coordination numbers and geometry given in Table 1. Nb$_4$AlC$_3$ and Nb$_4$C$_3$T$_x$ contain two distinct crystallographic Nb sites and two C sites. Nb2 and C2 are the sites nearer to the Al/etched layer and will thus be referred to as ‘external’ while Nb1 and C1 are denoted ‘internal’ following the assignments in the Inorganic Crystal Structure Database crystal structure files 160755$^{21}$ and 606236$^{19}$. Nb$_2$AlC and Nb$_2$CT$_x$ contain one Nb site and one C site; these are necessarily ‘external’. Both MAX phases contain a single Al environment with
trigonal prismatic coordination to six niobium atoms. Note that the MXene coordination in Table 1 is described in the absence of termination groups (T).

<table>
<thead>
<tr>
<th>Compound</th>
<th>Nb1 Coordination by Crystallographic Site</th>
<th>Nb2</th>
<th>Al</th>
<th>C1</th>
<th>C2</th>
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<tbody>
<tr>
<td>Nb₂AlC</td>
<td>fac-NbAl₃C₃ (D)</td>
<td>−</td>
<td>AlNb₆ (P)</td>
<td>CNb₆ (R)</td>
<td>−</td>
</tr>
<tr>
<td>Nb₃AlC₃</td>
<td>NbC₆ (R)</td>
<td>fac-NbAl₃C₃ (D)</td>
<td>AlNb₆ (P)</td>
<td>CNb₆ (R)</td>
<td>CNb₆ (R)</td>
</tr>
<tr>
<td>Nb₂C</td>
<td>NbC₃ (T)</td>
<td>−</td>
<td>−</td>
<td>CNb₆ (R)</td>
<td>−</td>
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<tr>
<td>Nb₂C₂</td>
<td>NbC₃ (T)</td>
<td>NbC₃ (T)</td>
<td>−</td>
<td>CNb₆ (R)</td>
<td>CNb₆ (R)</td>
</tr>
</tbody>
</table>

D = distorted octahedron; R = regular octahedron; T = trigonal pyramid; P = prismatic.

Solid-state NMR spectroscopy is a versatile toolkit that is sensitive to bonding and electronic properties with the ability to probe different elements individually. Additionally, there is no requirement for long-range periodic order in NMR, therefore, it can be readily applied to defect and surface chemistry as well as to nanoparticles. In particular, NMR can reveal the presence of amorphous impurities which are invisible to diffraction techniques. All the elements in the niobium aluminum carbide phases are NMR active and relatively accessible: ¹³C is I = ½ with a natural abundance of 1.1%, while ⁹³Nb (I = 9/2) and ²⁷Al (I = 5/2) are 100% naturally abundant quadrupolar nuclei. The quadrupolar nature of the latter two nuclei means that they are extremely sensitive to the symmetry of their local environment. Despite the analytical utility, NMR investigations of MAX and MXene phases are sparse. Lue et al. measured static ²⁷Al NMR spectra of the 3d transition metal MAX series Ti₂AlC, V₂AlC, and Cr₂AlC, finding relatively long nuclear relaxation times and systematically decreasing nuclear quadrupole coupling constants and Knight shifts from Ti toward Cr. The first NMR study of a MXene was by Harris et al. who identified –OH and –F surface terminations in V₂C by ¹H and ¹⁹F NMR spectroscopy and demonstrated the proximity of ¹H nuclei to the MXene surfaces by using ¹H→¹³C cross polarization (CP). Hope et al. later quantified the concentrations of –OH and –F terminations on Ti₃C₂ MXene, which were found to be highly dependent on the synthesis method, and showed the terminations to be intimately mixed using ¹H–¹⁹F NMR
correlation experiments.\textsuperscript{33} These observations have been extended to further Ti\textsubscript{3}C\textsubscript{2}T\textsubscript{x} syntheses and preparation conditions in a pair of very recent reports.\textsuperscript{34,35}

In this work, a comprehensive multinuclear NMR study \((^{93}\text{Nb}, ^{27}\text{Al}, ^{13}\text{C}, ^{1}\text{H}, \text{and} ^{19}\text{F})\) of the bulk structures and surface chemistry of the known Nb\(_{n+1}\)AlC\(_n\) MAX and Nb\(_{n+1}\)C\(_n\)T\(_x\) MXene phases is performed with a range of one- and two-dimensional techniques, with additional comparisons to Nb\(_2\)SnC and the \(^{47/49}\text{Ti}\) NMR of Ti\(_3\)AlC\(_2\) MAX phase. These experiments are supported by DFT-based electronic structure calculations of the electric field gradient (EFG) at the nucleus. The quadrupolar parameters determined by high-resolution magic-angle spinning (MAS) and static wideline \(^{93}\text{Nb}\) and \(^{27}\text{Al}\) spectra give insights on the local structures of the MAX phases, while \(^{93}\text{Nb}\) and \(^{13}\text{C}\) spectra reveal the nature of the etching to the corresponding MXene phases, with the \(^{93}\text{Nb}\) NMR further confirming that the latter are surface terminated. \(^{1}\text{H}, ^{19}\text{F}\) and \(^{93}\text{Nb}\) two-dimensional NMR spectroscopy then identifies the chemistry and connectivity of the MXene surface terminations. Finally, the presence of diffraction-silent side-products is confirmed, including the observation of aluminum oxides via the \(^{27}\text{Al}\) NMR spectra. Overall, these results have important implications for the synthesis, characterization, and functional properties of Nb MAX and MXene phases.

**Experimental**

**Synthesis.** Nb\(_2\)AlC MAX phase was prepared as described per Naguib et al.\textsuperscript{22} Elemental powders of niobium (99.9\% metals basis, 325 mesh), aluminum (99.8\% purity, 300 mesh), and carbon black (99\% purity, 300 mesh) were mixed in a plastic jar with a ratio of 2:1.1:1 Nb:Al:C and ball milled. The powder was placed into an alumina boat and heated under Ar flow to 1600 °C, with a ramp rate of 4 °C·min\(^{-1}\), and sintered for 4 h. After natural cooling to room temperature, the MAX phase was milled into powder and sieved through a 400-mesh sieve.
To prepare Nb$_2$CT, MXene, 1.0 g of Nb$_2$AlC powder was transferred into 20 mL of HF (aqueous, 49%, Millipore-Sigma) over 60 s and stirred for 48 h at 50 °C. The mixture was washed several times by centrifugation at 3500 rpm (5 min/cycle), the supernatant was decanted, and deionized (DI) water was added until the supernatant reached a pH >6. Multilayered MXene powder was collected by filtration through a cellulose acetate membrane (0.45 µm pore size). The delamination of Nb$_2$CT was carried out by transferring 1.0 g of MXene powder into 10 mL of a diluted tetramethylammonium hydroxide (TMAOH) solution (25% in H$_2$O, Millipore-Sigma). The solution was stirred overnight (~18 h) at room temperature. To remove excess TMAOH, the mixture was washed by centrifugation with DI water (50 mL) at 3500 rpm for 20 min followed by decantation of the supernatant. The process was repeated until the supernatant reached a pH <8. Then, the sediment was dispersed in 50 mL of deionized water and sonicated for 1 h in an ice-bath with Ar bubbling. Finally, the mixture was centrifuged for 1 h at 3500 rpm, and the supernatant was carefully removed to leave the MXene sediment in the bottom of the tube.

To prepare Nb$_4$AlC$_3$, powders of niobium (99.9% metals basis, 325 mesh), aluminum (99.8% purity, 300 mesh), and carbon black (99% purity, 300 mesh) were mixed and the synthesis was performed as previously reported. To prepare Nb$_4$C$_3$T$_x$, 0.4 g Nb$_4$AlC$_3$ powder was added to 30 mL HF solution (aqueous, 49%, Millipore-Sigma) and stirred at room temperature (20–25 °C) for 6 days. The produced acidic mixture was washed by DI water followed by centrifugation (3500 rpm, 2 min per cycle). After each centrifugation cycle, the supernatant was discarded, and the sediment was dispersed in DI water until neutral pH (~7) was reached. In order to delaminate the Nb$_4$C$_3$T$_x$, 1 mL of TMAOH (25% in H$_2$O, Millipore-Sigma) was mixed with 9 mL DI H$_2$O, added to Nb$_4$C$_3$T$_x$, and shaken for 15 minutes at room temperature. The excess TMAOH was separated from the product by repeated centrifugation at 3500 rpm.
**Diffraction.** X-ray diffraction (XRD) patterns were recorded in reflection mode under sample rotation on a PANalytical Empyrean diffractometer with a Cu Kα (1.540598 Å + 1.544426 Å) X-ray source.

**Solid-state NMR Spectroscopy.** $^1$H, $^{13}$C and $^{19}$F spectra were recorded at 11.75 T. $^1$H and $^{19}$F spectra were recorded with a Hahn echo pulse sequence, or by taking the isotropic slice of a magic angle turning, phase adjusted spinning sideband (MATPASS) sideband-separation experiment. $^{36}$ $^1$H and $^{19}$F experiments were performed at 50 kHz MAS in a 1.3 mm HX probe with recycle delays of 15 s and 0.3 s, respectively. $^{13}$C spectra were recorded in a 2.5 mm HX probe at 25 kHz MAS, with a 1 s recycle delay and a Hahn echo pulse sequence; the MAX samples were diluted with 20 wt% boron nitride to facilitate spinning (of these metallic samples). $^1$H/$^{93}$Nb and $^{19}$F/$^{93}$Nb TRAPDOR experiments were performed at 25 kHz with a 2.5 mm HX probe and a recycle delay of 1 s. $^1$H/$^{19}$F HECTOR experiments were performed at 20 kHz with a 2.5 mm HX probe with recycle delays of 1 s or 3 s. $^{27}$Al and $^{93}$Nb spectra were recorded at 16.4 T with a 1.3 mm or 4.0 mm HXY probe under static or MAS conditions with a single pulse or a Hahn echo pulse sequence and a recycle delay of 0.3–100 s for $^{27}$Al and 0.1–0.5 s for $^{93}$Nb, as described in each figure. Broad static $^{93}$Nb spectra were collected with the assistance of an external automatic tuning/matching (eATM) robot $^{37}$. These variable-offset cumulative spectra (VOCS) measurements were recorded in steps of 170 kHz (~1000 ppm). $^{47,49}$Ti spectra were recorded with a CPMG pulse sequence using VOCS acquisition in steps of 80 kHz (~2000 ppm) with 115 echoes of 0.8 ms each and recycle delays of 0.1 s; the sub-spectra were combined by taking the skyline projection: $^{38}$ for each point, the highest intensity value from the overlapping sub-spectra is taken, rather than adding their intensities together. $^1$H spectra were referenced to adamantane at 1.81 ppm, $^{13}$C spectra to the tertiary carbon of adamantane at 38.5 ppm, $^{19}$F spectra to LiF at −203 ppm, $^{27}$Al spectra to AlF$_3$ at −15 ppm, $^{93}$Nb spectra to LiNbO$_3$ at −1004 ppm $^{39}$, and $^{47/49}$Ti spectra to the $^{49}$Ti signal of SrTiO$_3$ at −843 ppm.
The isotropic shift $\delta_{\text{iso}}$ is defined in the Haeberlen convention $\delta_{\text{iso}} = \frac{\delta_{XX} + \delta_{YY} + \delta_{ZZ}}{3}$ with the chemical shift anisotropy $\delta_{\text{CSA}}$ defined as $\delta_{\text{CSA}} = \delta_{ZZ} - \delta_{\text{iso}}$ and the shift asymmetry $\eta_{\text{CSA}}$ defined as $\eta_{\text{CSA}} = \frac{\delta_{YY} - \delta_{XX}}{\delta_{ZZ} - \delta_{\text{iso}}}$. With these definitions, the principal components of the shift tensor are ordered such that $|\delta_{ZZ} - \delta_{\text{iso}}| \geq |\delta_{XX} - \delta_{\text{iso}}| \geq |\delta_{YY} - \delta_{\text{iso}}|$. *N.b.* This definition of $\delta_{\text{CSA}}$ is sometimes referred to as the reduced anisotropy, which is equal to 2/3 of the ‘full’ anisotropy $\Delta \delta = \delta_{ZZ} - \frac{\delta_{XX} + \delta_{YY}}{2}$ used by some authors and programs. The quadrupolar coupling constant, $C_Q$, is defined by the nuclear quadrupole moment $Q$ ($Q_{\text{Nb-93}} = 32(2)$ fm$^2$; $Q_{\text{Al-27}} = 14.66(10)$ fm$^2$) and the largest principal component $V_{ZZ}$ of the EFG at the nucleus according to $C_Q = \frac{eQV_{ZZ}}{h}$ where $e$ is the electric charge and $h$ is Planck’s constant. The quadrupolar asymmetry parameter $\eta_Q$ is also defined by the EFG tensor components as $\eta_Q = \frac{V_{XX} - V_{YY}}{V_{ZZ}}$ ordered such that $|V_{ZZ}| \geq |V_{YY}| \geq |V_{XX}|$. The Rose convention (ZYZ) was used to define the Euler angles relating the orientations of the shift and quadrupolar tensors.

**Calculations.** Density functional theory (DFT) calculations were performed with the CASTEP planewave pseudopotential code. The calculations used the Perdew–Burke–Ernzerhof (PBE) exchange–correlation functional and Vanderbilt ultrasoft pseudopotentials. MAX crystal structures were used as starting models. Prior to the EFG calculations, atomic positions were optimized (with lattice parameters held constant) until the force on any atom was smaller than 10 meV·Å$^{-1}$. All calculations used a planewave energy cut-off energy of 600 eV and a Monkhorst–Pack grid with a spacing finer than $2\pi \times 0.04$ Å$^{-1}$ to sample the Brillouin zone. Computed EFG parameters were used as the starting point to fit the experimental $^{27}\text{Al}$ and $^{93}\text{Nb}$ spectra.
Results and Discussion

MAX bulk structure characterization. XRD analysis of the Nb$_2$AlC sample (Figure S1) showed Nb$_4$AlC$_3$ as a minor (~5% from Rietveld refinement) secondary phase. No additional peaks were visible beyond those of the two MAX phases. The Nb$_4$AlC$_3$ diffraction pattern showed a NbC-like impurity (~8%) and a small, broad unindexed peak just above the background signal at 26.7°; no Nb$_2$AlC was detected in the Nb$_4$AlC$_3$ sample.
Al NMR spectra of the MAX phases Nb$_2$AlC and Nb$_4$AlC$_3$ are given in Figures 2 and 3, respectively. For each compound, a simultaneous fit was performed over the static and MAS spectra (Table 2). The DFT calculated quadrupolar parameters served as useful starting points to guide the fits (Table 2). Static spectra were sensitive to the value of the CSA while MAS removed CSA broadening and resulted in spectra that were more sensitive to the isotropic shift.

27$^\text{Al}$ NMR spectra of the MAX phases Nb$_2$AlC and Nb$_4$AlC$_3$ are given in Figures 2 and 3, respectively. For each compound, a simultaneous fit was performed over the static and MAS spectra (Table 2). The DFT calculated quadrupolar parameters served as useful starting points to guide the fits (Table 2). Static spectra were sensitive to the value of the CSA while MAS removed CSA broadening and resulted in spectra that were more sensitive to the isotropic shift.
and quadrupolar tensor. The positions of discontinuities in the powder lineshape from satellite transitions, where observed, were also used to determine the quadrupolar parameters. The calculated quadrupolar coupling constants matched the experimental values to within <5%.

In addition to aluminum in the MAX phases, $^{27}$Al NMR revealed the presence of secondary phases. At short recycle delays, the MAX phases, with fast spin-lattice, $T_1$, nuclear relaxation from conduction electrons, appear relatively pure (Figure S2–3). However, at longer free induction decay (FID) intervals, the relative intensities of the impurities increase; an indication that the impurities are diamagnetic with longer $T_1$ relaxation times. The Nb$_2$AlC sample exhibits an unexpected resonance at 16 ppm while the Nb$_4$AlC$_3$ sample shows three additional $^{27}$Al resonances at ca. 5, 17, and 115 ppm. The largest impurity in both samples is ascribed to octahedral AlO$_6$ environments as found in corundum alumina, on the basis of the shift (16–17 ppm), $C_Q$ (ca. 2.4 MHz, upper limit ≤4 MHz) and $T_1$ relaxation time (18 s). The Nb$_4$AlC$_3$ sample signal at 5 ppm is also consistent with octahedral AlO$_6$, as found in e.g. boehmite, gibbsite, or γ-alumina.

The oxide environments could arise from secondary oxide phases, or from the oxide layers previously observed by XPS to form on the surface of MAX particles. The resonance at 115 ppm appears at a higher...
frequency than for typical aluminum oxides or fluorides\textsuperscript{48}; it does coincide with the shift range of aluminum carbide Al\textsubscript{4}C\textsubscript{3} (111–120 ppm) but the maximum $C_Q$ value for the observed resonance is ca. 4.5 MHz while Al\textsubscript{4}C\textsubscript{3} has two Al sites with $C_Q$ magnitudes of 14–17 MHz.\textsuperscript{49,50} Hayes et al. identified aluminum oxycarbide impurities with smaller $C_Q$s in their recent study of commercial Al\textsubscript{4}C\textsubscript{3} so a related aluminum species is plausible here.\textsuperscript{50} Another possibility is the tetrahedral aluminum nitride environment that appears at around 110–115 ppm in AlN and in aluminum oxynitrides with a $C_Q$ of a few MHz, consistent with the resonance observed here.\textsuperscript{51–54} Note that the $^{27}$Al signal from Nb\textsubscript{2}AlC covers a range of ~90–170 ppm, so the impurity at 115 ppm is less pronounced but it can be clearly seen as a shoulder that appears as the interval between scans increases (Figure S2). Quantitative spectra recorded with recycle delays of 90–100 s (Figure S2) revealed the relative ratios of the MAX and impurity (or surface) species in the samples from the perspective of aluminum content.\textsuperscript{37} For the Nb\textsubscript{2}AlC sample, a ratio of 89:9:2 was found for the MAX signal at 169 ppm and the impurity resonances at 16 and 115 ppm, respectively. For the Nb\textsubscript{4}AlC\textsubscript{3} sample, a ratio of 56:34:7:3 was found for the MAX signal at 319 ppm and the impurity resonances at 17, 5, and 115 ppm, respectively.

Table 2 – Experimental (shift and quadrupolar) and calculated (quadrupolar only) NMR parameters of Nb\textsubscript{2}AlC and Nb\textsubscript{4}AlC\textsubscript{3}.\textsuperscript{a} See Table S1 for chemical shift tensor component values in the standard convention.

<table>
<thead>
<tr>
<th>Phase</th>
<th>Site</th>
<th>$\delta_{\text{iso}}$ (ppm)</th>
<th>$\delta_{\text{CSA}}$</th>
<th>$\eta_{\text{CSA}}$</th>
<th>$C_Q$ (MHz)</th>
<th>$\eta_Q$</th>
<th>Euler angles</th>
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<td></td>
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<td></td>
<td>Exp.</td>
<td>Calc.$^b$</td>
<td>Exp.</td>
<td>Calc.</td>
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<td>$-475(10)^d$</td>
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<td>0.01(1)</td>
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\textsuperscript{a} Static and magic angle spinning spectra (in some cases at multiple fields) were fit to a single model. Estimated errors in the last digit are given in parentheses, derived from lineshape fitting.

\textsuperscript{b} The sign of the quadrupolar coupling can be calculated but is not determined experimentally from the spectrum of a polycrystalline sample.
The fits are only sensitive to the $\beta$ angle because $\eta$ is nearly zero.

The isotropic shift is temperature-dependent and thus varies with MAS rate. The static $^{93}$Nb spectrum of Nb$_2$AlC was fit with $-475(10)$ ppm while the 50 kHz spectrum was fit with $-445(5)$ ppm.

n/d = not determined, either due to insufficient signal-to-noise ($^{13}$C) or because the fit was insensitive to this parameter.

Cells corresponding to the quadrupolar properties are left blank for $^{13}$C because it is a $I = \frac{1}{2}$ nucleus.

Quadrupolar $^{93}$Nb NMR spectra of the compounds were recorded under MAS and static conditions. A fit of the $^{93}$Nb NMR data of Nb$_2$AlC reproduced the central and satellite transitions of the spectrum (Figure 4, Table 2), with calculated and measured nuclear quadrupolar coupling constants in close agreement. The Hahn echo and quadrupolar Carr–Purcell–Meiboom–Gill (QCPMG) $^{93}$Nb MAS spectra of Nb$_4$AlC$_3$ (Figure 5) showed a number of overlapping peaks that could not be resolved by variable MAS rates due to their individual linewidths (full-width at half-maximum (FWHM) > 40 kHz) and the static spectrum also showed overlapping lineshapes (Figure S4). To overcome this challenge, a MATPASS experiment was performed; the isotropic slice showed three broad, featureless resonances at $-840$, $-1700$, and $-2340$ ppm (Figure 5). However, only two distinct Nb environments are expected in Nb$_4$AlC$_3$. The low frequency $^{93}$Nb resonance matches that of NbC (Figure 5a,b, Figure S5a), as do the $^{13}$C NMR data (vide infra). Stoichiometric NbC should give a sharp $^{93}$Nb signal with $C_Q = 0$ due to the cubic site symmetry of the 12-coordinate niobium atom, however nonstoichiometry is common in NbC,$^{55}$ depending on the preparation conditions, with NbC$_x$ ($0.7 \leq x < 1$) yielding
quadrupolar $^{93}$Nb signals. Overlapping lines preclude an accurate fitting of the quadrupolar parameters of the NbC$_x$ impurity in Nb$_4$AlC$_3$ here but a small $C_Q$ (~2 MHz) is consistent with the lineshape. For Nb$_2$SnC (Figure S6), a sharp $^{93}$Nb signal was observed with an isotropic shift of ~189(3) ppm; this is 300 ppm higher frequency than the isostructural Nb$_2$AlC. In the wideline static VOCS measurement, Nb metal was also observed as a secondary phase at ~7200 ppm.

The $^{13}$C NMR spectrum of Nb$_2$AlC (Figure 6a, bottom) shows a single resonance at 293 ppm corresponding to the single carbon environment in the 211 phase. The $^{13}$C NMR spectrum of Nb$_4$AlC$_3$ (Figure 6b, bottom) shows two resonances at 324 ppm and 238 ppm corresponding to the outer (C2) and inner (C1) carbon sites of Nb$_4$AlC$_3$, respectively. For both Nb MAX phases, the large $^{13}$C shift is evidence of metallic conduction resulting in a Knight shift; the shifts are larger than observed for V$_2$AlC (208 ppm), but less than for Ti$_3$AlC$_2$ (566 ppm). There is a significant shoulder for the 324 ppm peak which is ascribed to NbC, the single carbon site of which resonates at ~315 ppm (Figure S5b,c); accounting for this signal, the integrated intensities of the inner and outer carbon sites are in reasonable agreement with the expected 2:1 ratio. The $^{13}$C and $^{93}$Nb data together clearly show the presence of NbC in
Nb₄AlC₃, although it is not observed in the X-ray diffraction pattern (Figure S1) because (i) it is present in nanoparticulate or amorphous form and/or (ii) its identification is obstructed by peak overlap. Note, that phases such as amorphous carbon and low levels of Nb₂O₅ would be difficult to observe via these NMR experiments due to the broad nature of those signals and/or overlap with other signals. The presence of alumina suggests that niobia could also be present, and Sarycheva and Gogotsi observed amorphous carbon and titania in a degraded Ti₃C₂Tx sample via Raman spectroscopy.⁵⁸

**MXene bulk structure characterization**

By etching out the aluminum, the MAX phases were converted to MXenes. However, the Nb₂CTₓ also has a significant amount of unreacted Nb₂AlC, while NbC remains present as an impurity in Nb₄C₃Tx, as previously seen for other MAX/MXene samples.²³,⁵⁹

The ⁹³Nb NMR spectra of Nb₂CTₓ and Nb₄C₃Tx are shown in Figure 7 and Figure S7. Since niobium atoms are located at the outer surface of the 2D MXene sheets, the number of distinct Nb local environments and NMR signals depends on the surface terminations. The ⁹³Nb lineshape of Nb₂CTₓ was simulated with two quadrupolar lines, providing a reasonable fit to the data (Figure 7); the minor but sharper signal is consistent with Nb₂AlC, the broader signal was attributed to Nb₂CTₓ and was fit with δiso = -790(30) ppm, CSA = -350(50) ppm, ηCSA = 0.5(3), CQ = 77(3) MHz, ηQ = 0.2(1), Euler angles α,β,γ = 0°, 50(10)°, 0°. The CQ for Nb₂CTₓ is more than double that of Nb₂AlC, providing spectral evidence for the reduction of symmetry at the MXene surface. Furthermore, the non-zero ηQ indicates a breaking of the three-fold symmetry of the Nb site at the surface, presumably due to the surface terminations. Calculations for a bare Nb₂C surface predict a ⁹³Nb CQ of 122 MHz, so the lower observed CQ is also evidence for the surface terminations which result in a more symmetric charge distribution than a bare surface. Basic ordered models for surface-terminated Nb₂CTₓ (Tₓ = F₂,
(OH), (OH)F, O2, O) give calculated CQ values ranging from 36–109 MHz (Table S2), which are consistent with the experimental CQ of 77 MHz. The best agreement is for fluoride and oxide termination, which may suggest a greater proportion of fluoride and oxide terminations than hydroxyl terminations, as previously observed for Ti3C2Tx.33 Meanwhile, the 93Nb lineshape of Nb4C3Tx is substantially broader. An exact fitting of the lineshape could not be obtained due to the difficulty of distinguishing a potential distribution of surface terminations, the two Nb sites in Nb4C3Tx, and the NbCx impurity, which all overlap. Nevertheless, based on the linewidth a maximum CQ of ~100 MHz can be determined, ruling out a significant proportion of bare surface (calculated CQ = 135 MHz for the outer Nb2 site, Table S3). Given that the calculated quadrupolar parameters for ordered models of surface terminations (Table S3) are in the range 15–70 MHz, chemical shift dispersion and anisotropy of the different Nb environments must make a large contribution to the experimental linewidth.

In the 13C NMR spectra of etched Nb2AlC, a new signal can be seen at 430 ppm due to Nb2CTx MXene, although there is also still unreacted Nb2AlC present (Figure 6a, top). The intensity in the 13C spectrum between the Nb2AlC and Nb2CTx resonances may correspond to partially etched regions with carbon environments intermediate between the MAX and MXene, e.g. regions with a MAX-like aluminum layer on
one side, but terminations on the other, or nanoscale clusters of unetched aluminum. After etching Nb$_4$AlC$_3$ (Figure 6b, top), a broad high frequency signal can be observed at ~400 ppm, corresponding to Nb$_4$C$_3$T$_x$ MXene, although the inner and outer carbon sites cannot be resolved. After etching, the NbC impurity is still evident, as well as signals from other impurities in the sample at 31 and 111 ppm; the former is correlated with a $^1$H signal at 1 ppm in the $^1$H→$^{13}$C HETCOR spectrum (Figure S8c), suggesting that this impurity is predominantly alkyl, while the latter can be observed in a $^{19}$F→$^{13}$C cross polarization (CP) experiment (Figure S8b), which, combined with the chemical shift, suggests a –CF$_2$– moiety in a fluorinated organic species. Notably, the $^{13}$C shift increases on etching from the MAX to the MXene for both Nb$_2$CT$_x$ and Nb$_4$C$_3$T$_x$; this is due to an increased Knight shift, corresponding to an increased density of states at the Fermi level for the carbon atoms in the MXene phases. The same increase in $^{13}$C shift was observed for V$_2$CT$_x$ (from 208 ppm to 260 ppm),$^{32}$ however, in contrast, the $^{13}$C Knight shift actually decreases for Ti$_3$C$_2$T$_x$ (from 566 ppm to 380–410 ppm)$^{33}$. A decrease in $^{13}$C shift was also observed on etching Mo$_2$Ga$_2$C to Mo$_2$Ct$_x$ (from 178 ppm to 125 ppm),$^{61}$ although in this case the shift is well within the diamagnetic range, implying there is not a significant density of states at the Fermi level localized on the carbons.

As seen from the presence of the Nb$_2$AlC MAX signal in the $^{93}$Nb, $^{27}$Al, and $^{13}$C spectra, not all aluminum had been etched out during the HF treatment, consistent with prior work on other MXenes: V$_2$AlC was observed in V$_2$CT$_x$ samples and Ti$_3$AlC$_2$ in Ti$_3$C$_2$T$_x$ samples in their respective $^{13}$C NMR spectra.$^{32,33}$ The $^{27}$Al NMR spectra of the MXene samples (Figure S9) also show an AlO$_6$-like aluminum oxide environment, while the Nb$_2$CT$_x$ sample also shows a signal consistent with AlF$_3$·nH$_2$O, a common impurity in MXenes$^{60}$ and one that can be readily identified with NMR spectroscopy.

Since diffraction did not reveal the Al–O, Al–F, or Al–(C,N,O) compounds identified here, these secondary phases must be amorphous, present as small nanoparticles, or hidden
under the MAX/MXene diffraction peaks. These findings again highlight that the picture from diffraction alone can be misleading. Furthermore, NbC₃ was almost entirely hidden under the Nb₄AlC₃ XRD peaks. A method that is sensitive to amorphous phases such as solid-state NMR and/or quantitative diffraction with an internal standard should be routinely performed to characterize MAX and MXene phases.

**Surface terminations of Nb₄C₃Tₓ and Nb₂CTₓ.** ¹H and ¹⁹F NMR spectra were recorded in order to investigate the surface functionalization of the MXene phases directly. The ¹H NMR spectrum of Nb₂CTₓ as synthesized shows a large signal at 6.3 ppm due to free H₂O as well as two resonances at large chemical shifts of 19.5 and 26.0 ppm (Figure 8a); these latter signals are assigned to –OH surface terminations. –OH terminations were observed in the MXenes V₂CTₓ at 85 and 27 ppm and Ti₃C₂Tₓ between 12.5 and 20 ppm, the exact shift values depending on the synthesis procedure. The free H₂O signal can be reduced by drying the MXene at 200 °C *in vacuo* (Figure 8b), after which an additional resonance can be distinguished at 12.2 ppm, as well as sharper signals between −0.5 and 1.6 ppm; the former could be due to a further –OH termination environment, or bound H₂O partaking in strong hydrogen bonding, while the latter are assigned to intercalated volatile contaminants, as was also observed for Ti₃C₂Tₓ. There is also a loss of intensity for the 26.0 ppm signal in particular, which may be due to loss of –OH terminations as H₂O during the drying process.
Figure 8 – $^1$H and $^{19}$F NMR spectra of Nb$_2$CT$_x$ (a–f) and Nb$_4$C$_3$T$_x$ (g–l). The $^1$H/$^{93}$Nb and $^{19}$F/$^{93}$Nb TRAPDOR difference spectra (c,f,i,l) show $^1$H (c,i) or $^{19}$F (f,l) atoms near $^{93}$Nb atoms. The echo and MATPASS experiments were performed at 50 kHz MAS and the TRAPDOR experiments at 30 kHz, all at a magnetic field strength of 11.7 T. Sidebands are marked with asterisks.
The assignment of the $^1$H NMR resonances at high chemical shift to surface species on the MXene layers can be confirmed by $^1$H/$^{93}$Nb TRAPDOR experiments. For these spectra, a $^1$H spin echo is recorded with continuous irradiation of $^{93}$Nb during only the first half of the echo, thus any dephasing due to recoupled $^1$H–$^{93}$Nb interactions is only partially refocused, resulting in a loss of signal intensity for $^1$H environments in the vicinity of $^{93}$Nb; when the difference is taken between spin echoes recorded with and without $^{93}$Nb irradiation, these $^1$H environments (near $^{93}$Nb) can be selectively observed. The signals at 12.2, 19.5 and 26.0 ppm can all be clearly observed in the TRAPDOR difference spectra (Figure 8c and Figure S10), confirming their vicinity to Nb atoms at the MXene surface; the signals at less than 5 ppm, on the other hand, are suppressed in the TRAPDOR difference spectra. A weaker TRAPDOR effect is observed for the free H$_2$O resonance at 6.3 ppm, which suggests that only some of the free H$_2$O is proximal to Nb and/or that it is mobile; this may be evidence of chemisorbed water, as proposed by Persson et al.

The sideband-separated $^{19}$F NMR spectrum of Nb$_2$CT$_x$, recorded with a MATPASS pulse sequence, shows a number of different resonances (Figure 8d). The signal at −158 ppm is due to AlF$_3$·nH$_2$O, a by-product of the etching process also seen in the $^{27}$Al spectrum (Figure S8); this resonance is suppressed in the $^{19}$F/$^{93}$Nb TRAPDOR difference spectrum (Figure 8f), leaving the signals at −20, −132 and −330 ppm, which must be near Nb. $^1$H/$^{19}$F HETCOR experiments (Figure S11) are completely dominated by the H$_2$O→AlF$_3$ correlation, so cannot be used to aid assignment of the $^{19}$F spectrum. After drying at 200 °C in vacuo the AlF$_3$·nH$_2$O resonance shifts to −164 ppm due to changes in hydration, so that the −132 ppm signal can be seen as a shoulder more clearly, and there is also a small, sharp peak at −121 ppm from a fluorinated organic impurity. The $^{19}$F signal at −20 ppm is largely removed by drying, so may be tentatively ascribed to −F terminations with strong hydrogen bonding to H$_2$O molecules, or adjacent −OH terminations (given that the intensity of the −OH signals in the $^1$H NMR also
decreases on drying. Conversely, the major $^{19}$F signal at $-132$ ppm is assigned to $-F$ terminations without strong H bonding. The minor signal at $-330$ ppm is strongly ionic; it may be a niobium fluoride species formed as a byproduct from excessive etching and could therefore be minimized by using milder etching conditions.\textsuperscript{66}

The $^1$H NMR spectrum of Nb$_4$C$_3$T$_x$ (Figure 8g) is dominated by a peak at 1.0 ppm due to the organic impurity identified from the $^1$H→$^{13}$C HETCOR experiment (Figure S8c). Further $^1$H signals at 5.5 ppm and 15 ppm are assigned to H$_2$O and $-OH$ terminations, respectively. Both the organic contaminant and the H$_2$O signals can be reduced by drying \textit{in vacuo} at 200 °C overnight (Figure 8h), while the $-OH$ terminations can be identified in the $^1$H/$^{93}$Nb TRAPDOR difference spectrum (Figure 8i and Figure S10). In the TRAPDOR experiment, the 1.0 ppm peak is almost, but not entirely, suppressed; the residual signal and satellite peaks are due to the differential phase (Bloch–Siegert) shift\textsuperscript{67,68} introduced by $^{93}$Nb irradiation, which results in imperfect cancellation in the difference spectrum.

The $^{19}$F MATPASS NMR spectrum for Nb$_4$C$_3$T$_x$ is dominated by a resonance at $-121$ ppm (Figure 8j,k), which is consistent with the fluorinated impurity identified by $^{19}$F→$^{13}$C CP. Two other signals can also be distinguished, centered at ca. $-190$ and $-80$ ppm; these are assigned to $-F$ terminations as they can clearly be observed in the $^{19}$F/$^{93}$Nb TRAPDOR difference spectrum (Figure 8l), although the sidebands of the terminal $-F$ signals are unresolved. Further evidence for the assignment of the $-OH$ and $-F$ terminations can be seen in the $^1$H/$^{19}$F HETCOR spectra: in the $^{19}$F→$^1$H spectrum (Figure 9b) a broad correlation is observed between both the H$_2$O (6.0 ppm) and $-OH$ (15 ppm) $^1$H resonances and $^{19}$F intensity between ca. 50 and $-300$ ppm that corresponds to the signals from $-F$ terminations at $-190$ and $-80$ ppm, with unresolved spinning sidebands. This supports the assignments of the $^1$H and $^{19}$F spectra, as well as showing that the terminations are intimately mixed, rather than being
segregated into different regions, as also found for Ti$_3$C$_2$T$_x$.$^{33}$ In contrast, the $^1$H→$^{19}$F spectrum (Figure 9a) only shows correlation between the $^1$H H$_2$O (6.0 ppm) signal and the −80 ppm −F termination $^{19}$F signal. The lack of signal from the −OH terminations is ascribed to a short $^1$H $T_1p$ for this resonance, so that the transverse magnetization decays before developing significant cross polarization. The fact that the H$_2$O resonance correlates only with the −80 ppm $^{19}$F signal suggests that these −F termination environments are associated with interlayer water via hydrogen bonding, whereas those at −190 ppm are not. The higher frequency $^{19}$F shift observed for H-bonded −F terminations in Nb$_4$C$_3$Tx is also consistent with the assignment of the −20 ppm $^{19}$F signal in Nb$_2$CT$_x$ to strongly H-bonded −F terminations.

Table 3 shows a comparison of the shifts of the observed surface species for the different MXenes studied by $^1$H and $^{19}$F NMR to date. For the −OH terminations, V$_2$CT$_x$ is the exception with an extremely large shift of 85 ppm; this is due to a metallic Knight shift, as confirmed by the short $T_1$ relaxation of this signal.$^{32}$ Interestingly, the −F terminations of V$_2$CT$_x$ do not appear to be significantly Knight shifted and are observed at a similar frequency to those
of Ti$_3$C$_2$T$_x$. The $^{1}$H shifts obtained for Ti$_3$C$_2$T$_x$ have been shown by both Hope et al.$^{33}$ and Anayee et al.$^{34}$ to depend on the synthesis procedure, but in both cases fall in the range 12.5–20 ppm. In contrast, Kobayashi et al.$^{35}$ observed no $^1$H signals at frequencies above 7 ppm, instead ascribing signals at 0.5–2.0 and 3.6 ppm to $-OH$ terminations on the basis of DFT calculations and the assignment of a Ti$_2$C$_x$ $^1$H spectrum in a separate report by Sugahara$^{69}$. These differences may be due to sample preparation, however, we note that the studies of Kobayashi et al. and Sugahara et al. do not provide direct evidence for their terminal $-OH$ assignments (c.f. the $^1$H–$^{13}$C HETCOR employed for V$_2$C$_x$ and Ti$_3$C$_x$,$^{32,33}$ and the $^1$H($^{93}$Nb) TRAPDOR used here). Furthermore, (i) Sugahara et al. found an estimated composition of Ti$_2$C(OH)$_{0.3}$O$_{0.7}$F$_{0.6}$Cl$_{0.4}$ with a similar etching procedure to Kobayashi et al. (LiF, HCl)$^{69}$ and (ii) Ti$_3$C$_2$T$_x$ is electronically conducting (so much so that the sample in the Kobayashi et al. study was diluted by a factor of 20 to perform magic angle spinning) but the DFT calculations for $-OH$ shifts include neither $-F$ termination nor Knight shift contributions, which are expected to substantially affect the $^1$H shifts.$^{35}$ It is possible that due to the high conductivity of their samples, Kobayashi et al. and Sugahara et al. are not able to observe the $-OH$ terminations due to rf penetration or bulk magnetic susceptibility broadening effects.

The $-OH$ $^1$H shifts for the Nb MXenes are similar to those observed for Ti$_3$C$_2$T$_x$ by Hope et al.$^{33}$ and Anayee et al.$^{34}$, although as the 26 ppm signal for Nb$_2$CT$_x$ is outside the diamagnetic range for $^1$H NMR, there must also be at least a small Knight shift, as for V$_2$CT$_x$. The $-F$ terminations, on the other hand, are observed at higher frequencies for the Nb MXenes than for V$_2$C$_x$ and Ti$_3$C$_2$T$_x$, which could be due to more covalent Nb–F bonding caused by the more diffuse 4$d$ orbitals. In general, the multiple NMR signals observed for $-OH$ and $-F$ terminations, and the dependence on the synthesis, can be ascribed to distinct local environments due to different arrangements of the surface terminations ($-OH$, $-O$, $-F$ and
termination vacancy), as well as interlayer H₂O, as shown, for instance, for the –F terminations in Nb₄C₃Tx.

Table 3 – Summary of the chemical shifts of ¹H and ¹⁹F surface species observed for different MXenes.

<table>
<thead>
<tr>
<th>Phase</th>
<th>Source</th>
<th>δ¹H /ppm</th>
<th>δ¹⁹F /ppm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nb₂CTₓ</td>
<td>This work</td>
<td>12.2, 19.5, 26.0</td>
<td>−20, −132</td>
</tr>
<tr>
<td>Nb₄C₃Tx</td>
<td>This work</td>
<td>15.0</td>
<td>−80, −190</td>
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<tr>
<td>V₂CTₓ</td>
<td>Harris et al.³²</td>
<td>27, 85</td>
<td>−265</td>
</tr>
<tr>
<td>Ti₃C₂Tx</td>
<td>Hope et al. ³³</td>
<td>12.5/18.6ᵃ</td>
<td>−227/−255ᵃ</td>
</tr>
<tr>
<td></td>
<td>Anayee et al.³⁴</td>
<td>15/20ᵃ</td>
<td>Not attempted</td>
</tr>
<tr>
<td></td>
<td>Kobayashi et al.³⁵</td>
<td>0.5–2.0, 3.6</td>
<td>“Unable to observe”³⁵</td>
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</table>

³ Depending on the synthesis procedure

Extending the transition-metal NMR of MAX phases. Based on insights gained from the ⁹³Nb NMR of Nb MAX phases, we were also able to interpret the ⁴⁷/⁴⁹Ti NMR of Ti₃AlC₂, another technologically important MAX phase used as a high temperature ceramic, and the precursor to the most studied MXene phase, Ti₃C₂Tx.⁷⁰,⁵,⁷ Ti NMR is particularly challenging to interpret because its two NMR-active isotopes, ⁴⁷Ti and ⁴⁹Ti, are both quadrupolar (I = ⁵/₂ and ⁷/₂, respectively) and by chance have extremely similar gyromagnetic ratios, differing by only 267 ppm (0.027%). As a result, overlapping quadrupolar lineshapes for both isotopes are typically observed in a single spectrum.⁴⁶,⁷¹–⁷³ Nevertheless, the ⁴⁷Ti and ⁴⁹Ti signals of both the inner
and outer Ti environments in Ti$_3$AlC$_2$ could be assigned from the overlapped spectrum (Figure 10) by considering that the $C_Q$ values for the outer/inner metal sites are expected to differ by an order-of-magnitude (c.f. $^{93}$Nb in Nb$_4$AlC$_3$), and by using the fixed relationships between the nuclear properties of $^{47/49}$Ti. The quadrupolar parameters of the two titanium sites for both nuclei are given in Table 4: since the frequency separation and ratio of the quadrupolar coupling constants for the $^{47}$Ti and $^{49}$Ti signals are fixed by their respective nuclear properties, there are fewer independent parameters than it might seem, and the simultaneous agreement of both signals with the measured spectrum affords a high confidence in the NMR parameters. As also observed for the Nb MAX phases (Table 2), the Ti sites exhibit axial quadrupolar tensors, consistent with the crystallographic symmetry, while the inner site has a modest $C_Q$ relative to the outer site.

Table 4 – Fitted $^{47}$Ti and $^{49}$Ti quadrupolar parameters for the two crystallographic Ti sites in Ti$_3$AlC$_2$ extracted from Figure 10. The estimated errors in the last digit are given in parentheses. Note that the simulated spectra were insensitive to the CSA parameters, which were therefore not determined.

<table>
<thead>
<tr>
<th>Site</th>
<th>Nucleus</th>
<th>$\delta_{iso}$ (ppm)$^a$</th>
<th>$C_Q$ (MHz)</th>
<th>$\eta_Q$</th>
</tr>
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<tr>
<td>Inner</td>
<td>$^{47}$Ti</td>
<td>$-27(10)$</td>
<td>2.57$^e$</td>
<td>0.00$^c$</td>
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<tr>
<td></td>
<td>$^{49}$Ti</td>
<td>239(10)</td>
<td>2.10$^e$</td>
<td>0.00$^c$</td>
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<tr>
<td>Outer</td>
<td>$^{47}$Ti</td>
<td>1338(20)</td>
<td>18.1(3)</td>
<td>0.00(5)</td>
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<tr>
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<td>$^{49}$Ti</td>
<td>1604(20)</td>
<td>14.8(2)</td>
<td>0.00(5)</td>
</tr>
</tbody>
</table>

$^a$The $^{47}$Ti shifts are referenced to $^{49}$Ti and as such are 266 ppm less than the corresponding $^{49}$Ti shift, rather than equal.
$^b$This represents an upper bound, based on the linewidth of the $^{47}$Ti signal.
$^c$The inherent linewidth is too broad to determine $\eta_Q$ from the lineshape of the central transition, and the turning points of the satellite transitions cannot be identified, however $\eta_Q = 0$ is consistent with the crystallographic symmetry.

Conclusions

An extensive survey of the NMR properties of the Nb MAX and MXene phases has been presented. The multinuclear approach adopted in this study provides complementary measurements of the local structural and electronic properties of the MAX and MXene phases, identifies the nature and connectivity of MXene surface terminating species, and enables unambiguous detection of a number of impurity phases.
$^{27}\text{Al}$ and $^{93}\text{Nb}$ NMR spectra of the MAX phases Nb$_2$AlC and Nb$_4$AlC$_3$ have been recorded under static and MAS conditions with high resolution and wideline techniques, allowing extraction of the full anisotropic shift and quadrupolar tensors. The insights gained from the Nb MAX phases also then enabled the interpretation of the $^{47/49}\text{Ti}$ spectrum of Ti$_3$AlC$_2$. The quadrupolar parameters extracted from the spectra were in close agreement with DFT calculations, affording a detailed view of the local coordination environments. The $^{27}\text{Al}$, $^{93}\text{Nb}$ and $^{13}\text{C}$ spectra also reveal impurity phases in both Nb$_2$AlC and Nb$_4$AlC$_3$, including aluminium oxide, hydrated aluminium fluoride, aluminium carbide/oxycarbide/nitride, niobium metal, and (possibly nonstoichiometric) NbC$_x$ species. Many of these impurities are not apparent from diffraction alone and these results should serve as a guide for future synthesis efforts.

Following the etching process, the conversion to form MXenes was confirmed by $^{13}\text{C}$ NMR, although the presence of unreacted Nb$_2$AlC is apparent in the $^{93}\text{Nb}$, $^{27}\text{Al}$, and $^{13}\text{C}$ spectra of the Nb$_2$CT$_x$ sample. $^{93}\text{Nb}$ environments become notably more asymmetric in the MXenes, demonstrating the reduction of symmetry at the surface. The quadrupolar coupling is still lower than calculated for a bare surface, however, pointing to the presence of surface terminations; these surface terminations are key in determining the performance of MXenes in various applications. –OH and –F terminations have been identified for both Nb$_2$CT$_x$ and Nb$_4$C$_3$T$_x$ in the $^1\text{H}$ and $^{19}\text{F}$ NMR spectra, their proximity to the surface demonstrated with $^{93}\text{Nb}$ TRAPDOR experiments, and a comparison made with previous studies on Ti$_3$C$_2$T$_x$ and V$_2$CT$_x$ MXenes. The atomic-scale intermixing of –OH and –F terminations for Nb$_4$C$_3$T$_x$ is seen in the $^1\text{H}/^{19}\text{F}$ HETCOR spectra, which would be challenging to identify by other techniques, and the different $^{19}\text{F}$ termination environments observed for both MXenes are correlated with the degree of hydrogen bonding to interlayer H$_2$O.
The structural insights derived here should serve as a basis to improve synthetic methods and to guide more in-depth computational modelling, both for the Nb MAX and MXene phases, as well as to facilitate comparisons with the wider family of materials. The nature of the surface terminations and interlayer water in MXenes are key to understanding the functional properties, while further insight into the electronic structure in the MAX phases is of fundamental interest. In this way, structure–property relationships can be developed and both MAX and MXene materials can be optimized for advanced functional applications.

Associated Content

Supplementary information file containing diffraction data; additional NMR spectra of Nb₄AlC₃, Nb₂AlC, Nb₄C₃Tx, Nb₂CTₓ, Nb₂SnC, and NbC; Nb MAX phase chemical shift tensors tabulated in the standard convention; tables of ⁹³Nb quadrupolar parameters for bare and terminated Nb MXene surfaces.

Author Information

Corresponding Author

Email: cpg27@cam.ac.uk

Notes

The authors declare no competing financial interest.

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For Table of Contents Only

Solid-state NMR  DFT
MAX  27Al
  13C
  28Nb
MXene