I. INTRODUCTION

In a sense, uranium tetrafluoride (UF₄)¹⁻⁷ is the simplified version of uranium dioxide (UO₂)¹⁻¹¹. While UO₂ is widely used as a nuclear fuel and is a key participant in nuclear storage scenarios, it is interlaced with complexity, including issues of 5f covalency.⁶ On the other hand, UF₄ tends to the more ionic limit.⁶ While the uranium species in both are isoelectronic, being U⁴⁺(5f²) if completely oxidized, the degree of oxidation depends on the oxidizing agent, with fluorine being the better oxidant. Uranium tetrafluoride does have the complication of lower symmetry and two inequivalent uranium sites per unit cell, but the UL₃ (2p1/2) extended x-ray absorption fine structure (EXAFS) measurements points toward essentially identical bond lengths between uranium and the oxidant.⁴ Thus, it is useful to pursue a spectroscopic interrogation of UF₄, with the intent to better understand both UF₄ and its more complicated cousin, UO₂.

In the process of carrying out this investigation of UF₄, some rather peculiar but interesting qualities were observed in the surface degraded parts of the single crystalline sample. The chief of these is the possible presence of a uranyl structure such as uranyl fluoride [U(VI)O₂F₂, with a UO₂²⁺ (VI) moiety] in a near-surface, but subsurface region (Fig. 1). However, it should be noted that the surface analysis presented herein is a bit unusual. In most surface analyses, one prepares a clean surface and then permits it to degrade, by monitoring the process. In the case of a radioactive sample at a user facility such as the advanced light source (ALS), there are concerns about the dissemination of radioactive debris. Thus, the experiment was pursued in a different approach, using a combination of photon and electron based probes to vary the sampling depth. In fact, one might liken this type of surface analysis to a forensics study, where the sample remains intact. The spectroscopic analysis will follow after a brief description of the experimental details.

II. EXPERIMENT

The x-ray absorption spectroscopy measurements were carried out at beamline (BL) 8.0 at the ALS at Lawrence Berkeley National Laboratory. For BL 8.0, energy calibrations were performed at the Fe 2p₃/₂ white line (710 eV for iron oxide) for the beamline monochromator. This calibration is reflected in the energy scale used in the regime around 700 eV: a 10 eV shift is invoked. However, it is less clear how to apply this shift to the energy regime near the OK (1s) threshold, around 500 eV. Thus, instead, we will quote the original energy scale of the beamline monochromator and then shift the spectra to place them on the same scale as spectra taken from the literature, as denoted below. Details of the BL 8.0 characteristics can be found in Ref. 13. Data were collected at room temperature (300 K). The uranium tetrafluoride was a single-crystalline sample, with significant surface degradation.⁶

Fig. 1. (Color online) Shown here is a series of OK (1s) x-ray absorption spectra for the uranium tetrafluoride sample and the carbon tape, using TFY and TEY detection. These data were smoothed and corrected for I₀.
The measurements to be discussed include x-ray absorption, x-ray emission, and x-ray photoelectron spectroscopy (XPS), the processes of which are shown schematically in Fig. 2. Because core level electrons are involved in these processes, there is a fundamental elemental specificity to the analysis. The specifics of each measurement will be briefly discussed in connection with the spectroscopic data in the figures below.

In the case of x-ray absorption spectroscopy, two variants will be utilized: total fluorescence yield (TFY) and total electron yield (TEY). In our case, the TEY was performed using a channeltron for electron detection.6,13 The experimental arrangements for these variants are shown diagrammatically in Fig. 3.

For the experiments on BL 8.0, the UF₄ sample was mounted on a sample platen with carbon tape, as shown in Fig. 4. This provided sufficient conductivity to avoid sample charging and allowed unhindered access to the UF₄ sample. Despite the blackish corrosion, note the hints of blue-green color from the underlying UF₄. The carbon tape was also used to determine background emission, as will be discussed below.

III. RESULTS AND DISCUSSION

A. Summary of earlier laboratory-based results

In a prior publication, XPS and x-ray emission spectroscopy (XES) were used to probe the nature of the uranium tetrafluoride sample.2,14 Some of these results are shown in Fig. 5. Here, the XES is performed utilizing an electron beam to generate core holes, the decay of which gives rise to the observed XES lines. The F K (1s) XES spectrum is shown as an inset, in the right side of the Fig. 5. The F K emission energy roughly corresponds to the to the F1s binding energy, because the decay process involves valence electrons dropping down into the core hole, consistent with the illustration in Fig. 2. While the F1s XES emission is strong and sharp, a strong F1s XPS feature is absent in the XPS spectrum.

In the XPS spectrum, there are strong but broadened features for the U4d and U4f levels, as well as clearly obvious O1s and C1s peaks. This suggests multiple U sites with significant chemical inhomogeneity. The oxygen and carbon
The features are a sure indication of surface degradation. Furthermore, the absence of a strong F1s feature argues for the absence of any significant amount of fluorine on the surface. There is one, or maybe are two, weak XPS features in the vicinity of where the F1s should be, but these are barely above the noise.

From these results and based upon the far greater surface sensitivity of XPS versus XES, it seems likely that while the interior of the sample is UF₄, the surface is not. Moreover, the surface is dominated by uranium-oxygen and -carbon species, the exact natures of which are unknown. This simplistic picture of the Uranium Fluoride sample is illustrated in the top panel of Fig. 4. However, as will be shown below, there is also evidence for a subsurface layer, with a different chemical nature.

**B. Synchrotron radiation results**

As part of the studies at the ALS, F K (1s) XAS was performed, the results of which are shown in Fig. 6. Here, both total fluorescence (TFY) and TEY were utilized for detection. Once again, it is expected that the TEY will be far more surface sensitive than the TFY. This expectation is borne out in the data. While the TEY is almost featureless with a poor signal-to-noise ratio, the TFY shows sharp, well-defined peaks with strong signal-to-noise. Furthermore, it has been demonstrated that the broad features in the middle range of the spectrum are F1s EXAFS, consistent with the U L₃ EXAFS of UF₄, which has been measured separately at much higher energies and clearly originates with the bulk."⁴,⁶ This F1s EXAFS strongly suggests that the bulk is an intact UF₄ structure, consistent with a UF₄ single crystal. Finally, the sharp features near threshold have been analyzed spectroscopically and are clearly associated with the F2pU⁵f and F2pU⁶d unoccupied density of states. So, once again, it is clear that there is significant surface degradation but an intact UF₄ underneath, in the bulk."⁶

Bearing all of this in mind, it was decided to look at the corrupted surface species using O 1s XAS, as can be seen in Figs. 1 and 7. Again, both TEY and TFY were used. Interestingly, the UF₄ TEY O K (1s) XAS spectrum is fairly similar to those of the carbon tape. (One might expect that the carbon tape spectra would be representative of chaotic surface oxidation. Consistent with that notion, both the TFY and TEY of the carbon tape are qualitatively the same, as can be observed in Fig. 1.) However, the UF₄ TFY O K (1s) spectrum has some additional spectral structure. In some
ways, this makes sense: the more surface sensitive detection (TEY) shows more pervasive and complete corruption than the less surface sensitive detection (TFY). At first thought, it might be possible that the species formed could be uranium dioxide, but that is clearly not the case. As shown in Fig. 7, the UO₂ TFY O K (1s) has a very different spectral structure than the UF₄ TFY O K (1s). [An extensive study of UO₂ clearly demonstrated that the UO₂ TFY O K (1s) spectrum is correct and representative of bulk UO₂.¹⁻] Intriguingly, the TEY spectra are similar, for both UO₂ and UF₄, indicative of related surface corruption in both cases.

This leaves the situation as follows. (1) From XES, TFY XAS, and EXAFS, it is clear that the bulk is intact UF₄, consistent with the single crystalline nature of the sample. (2) From XPS and TEY XAS, it is similarly clear that the surface region is corrupted, with no single clearly defined F species. (3) The O1s TFY XAS suggests the dominance of a single oxygen-related species in a subsurface but nonbulk environment, which is neither UF₄ nor UO₂, consistent with the model of Fig. 4. The goal of the remainder of this paper is to identify the species in (3).

Figure 8 shows a comparison between the UF₄ O K (1s) TFY XAS and the earlier results for UO₃, uranyl oxide, from Magnuson et al.¹⁵ Magnuson’s spectrum clearly shows a three peak structure that is in substantial agreement with the UF₄ TFY spectrum. Additionally, in Table I, peak energies and peak energies are compared for a series of samples. The uranyl fluoride and uranyl chloride, from Spectrochimica Acta and an online publication of Duffin et al.,¹⁶ have a distinct three peak spectral structure. Clark et al. of Los Alamos National Lab have also published online a similar three peak spectral structure for a series of uranyl moieties (AnO₂Cl₄)₂⁻, with An = U, Np, and Pu.¹⁷

The peak structures for the mixed moieties, particularly those of Duffin et al.,¹⁶ are sharper than those reported for the pure uranyl oxide, UO₃, but have similar peak positions and energy separations. These comparisons strongly suggest

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<td></td>
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<td>UF₄</td>
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Fig. 7. (Color online) Here are plotted a series of O K (1s) XAS spectra, using TFY and TEY, for UO₂ and UF₄. The UF₄ spectra have been shifted to maximize alignment with the UO₂ spectra. The UO₂ spectral energies were cross calibrated using the O K (1s) XAS in first, second, and third orders. The UO₂ spectra are taken from Ref. 9.

Fig. 8. (Color online) Comparison between the O K (1s) of UF₄ vs that of UO₃ from Magnuson et al. (Ref. 15). The topmost spectrum has been shifted to align with the Magnusson energy calibration.
Finally, it is useful to attempt to quantify the depth sensitivity of these measurements. To do so, one needs to consider the issue of mean free paths (MFP). The concept of mean free paths can be traced back to the kinetic theory of gases. For electrons in solids, the values will depend not only on the energies but also on the materials. As might be expected, the escape depths or penetration depths for electrons tend to be substantially less than those for photons. In the case of total electron yield measurements in XAS, which is dominated by low energy electrons, previous experimental results indicate a MFP of 22 Å or 2.2 nm. A consideration of the results in Ref. confirms that estimate, if one assumes an electron energy of about 10 eV. For the energies associated with the XPS measurements, a MFP of about 10 Å seems reasonable, again based on the results of Ref. 19. Thus, the sampling depth of the XPS and XAS measurements should be on the same scale of about 10–20 Å, with the XAS being perhaps a factor of two greater. This last detail may explain the observation of a F1s XAS peak with TEY but the absence of a significant F1s peak in XPS. One can expect that the photon measurements will penetrate far deeper, on the scale of micrometers (10,000 Å or 1000 nm). The qualitative nature of these estimates must be emphasized. Nevertheless, it is clear that the electrons are probing the near surface regime of nanometers and that the electrons are sampling far deeper into the bulk.

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IV. SUMMARY AND CONCLUSIONS

While the bulk of the single crystal sample remains intact UF4 and can be successfully interrogated with bulk-sensitive probes, the surface and subsurface regions are corrupted. The surface of the UF4 sample is so severely corrupted as to be essentially unrecognizable as originating from UF4. However, the subsurface seems to have a uranyl species, probably UO2F2, which may be a precursor on the path to the more total corruption of the surface region.