XPS Investigation of the Electrolyte Induced Stabilization of LiCoO$_2$ and "AlPO$_4$"-Coated LiCoO$_2$ Composite electrodes


http://dx.doi.org/10.1149/2.0851602jes

Electrochemical Society

Final published version

Sun Dec 16 12:28:00 EST 2018

http://hdl.handle.net/1721.1/109783

Creative Commons Attribution 4.0 International License

http://creativecommons.org/licenses/by/4.0/

The MIT Faculty has made this article openly available. Please share how this access benefits you. Your story matters.
Lithium cobalt oxide, LiCoO$_2$, is currently the most common cathode material used in lithium ion battery technology, but only half of the theoretical capacity, $\approx$140 mAh g$^{-1}$, is obtained when charged to 4.2 V vs. Li$^+$/Li. Higher capacity is obtainable if cycled to voltages greater than 4.2 V, but this was shown to result in high capacity loss. Structural instability and reactivity of the cathode with the electrolyte have both been proposed as possible mechanisms for the observed capacity fade. Surface modification via coatings with intrinsic materials by thermal treatment during the synthesis process or with extrinsic materials is one successful method of improving performance. These cathodes with surface-modified LiCoO$_2$ have shown improvement when cycled to high voltages compared to bare LiCoO$_2$ positive electrodes. However, the origin responsible for the increased performance is not well understood. Understanding the mechanism responsible for the enhancement in cycling stability provided by the coatings/surface modification is essential to further stabilize positive electrode materials for applications that demand high cycle life such as electrical vehicles and stationary storage.

Enhanced performance in cycling associated with surface coating has been attributed to phase transitions, suppression of electrolyte decomposition, reduced oxygen activity associated with cation mixing, physical barriers and HF scavenging, suppression of side reactions, electrolyte acidity, and the PVDF binder as a source of HF. The recent investigation by Daheron et al. showed that the substitution of Al for Co not only increases the ionic nature of the Co-O bond through orbital mixing, but also that the substitution reduces the basicity of the LiCoO$_2$ surface, thus making the surface less receptive or vulnerable to acidic attack in the electrolyte. However, this benefit can be temporary as recent work indicates that the Li-Al-Co-O surface region is consumed during cycling. The “AlPO$_4$”-coating on LiCoO$_2$ can induce the formation of Al-rich regions (Li$x$Al$_{1-x}$Co$_{2-x}$O$_4$) and P-rich regions (Li$^+$) conducting Li$_{2}$PO$_4$, and that Co- and Al-containing oxyfluoride species and species like PF$_x$(OH)$_y$ developed on the surface during cycling can lower the rate of Co dissolution and deposition of Co-containing species on the negative electrode and further degradation of LiPF$_6$. For a more detailed discussion of the metal fluoride formation mechanism, the reader is directed to Figure 12 and the corresponding discussion in the report by Lu et al.

In this paper, we examine the influence of the fluorine source on the formation of metal fluorides and the efficacy of the surface coating by relating cycling performance to the surface chemistries of bare and “AlPO$_4$”-coated LiCoO$_2$ electrodes cycled in 1 M LiPF$_6$ or LiClO$_4$ in EC:DMC (1:1) to 4.6 V. For a more detailed discussion of the metal fluoride formation mechanism, the reader is directed to Figure 12 and the corresponding discussion on page 4421 (second column) of Lu et al. The LiClO$_4$ salt was used to help determine if the formation of the metal fluorides was a product of the interaction between the active material with the LiPF$_6$ electrolyte and/or the PVDF binder. The contribution of the F-containing LiPF$_6$ salt on the efficacy of the surface coating in contrast to the non F-containing LiClO$_4$ salt will be discussed.

**Experimental**

Bare LiCoO$_2$ and “AlPO$_4$”-coated LiCoO$_2$ powder samples were prepared as previously described. The reversible capacities and cycling stability of bare and “AlPO$_4$”-coated LiCoO$_2$ composite electrodes were measured by using a two-electrode lithium cell (Tommel type TJ-AC). Lithium cells were constructed inside the glove box (H$_2$O, O$_2$, < 3 ppm, Mbraun, USA) using a lithium metal foil as the negative electrode and the composite positive electrode separated by two polypropylene microporous separators (Celgard 2500). The electrolytes used were 1 M LiPF$_6$ or 1 M LiClO$_4$ (battery grade, dry, 99.99% trace metals basis, Aldrich) in a 3:7 volume ratio EC/DMC solvent (Kishida Chemical Corp, Japan). The assembled lithium cells were set aside for 6 h prior to electrochemical testing on a Solartron 1470 battery testing unit in order for the electrolyte to wet the electrodes. The cells with bare and coated LiCoO$_2$ electrodes were cycled at the C/5 rate between voltage limits of 2.0–4.6 V with 4 h hold at 4.6 V for 20 cycles. The C-rate was defined based on the theoretical capacity of LiCoO$_2$ (274 mA h g$^{-1}$). The discharged cells were disassembled in the glove box, after which the Li$_{2}$CO$_3$ electrodes were extracted and stored in hermetically sealed containers in the glove box.

The XPS spectra of bare and “AlPO$_4$”-coated LiCoO$_2$ electrodes before and after cycling were measured using a Physical Electronics model 5400 X-ray photoelectron spectrometer. Each electrode was removed from the hermetically sealed container in an argon-filled glove box ($<$ 3 ppm O$_2$, < 3.5 ppm H$_2$O) and mounted onto the sample puck.
with the aid of copper clips placed on the edge of the electrode. The electrode was then transferred via a sealed chamber to the introduction chamber of the XPS spectrometer without exposure to ambient conditions. The introduction chamber was evacuated for 10–15 min before the sealed chamber was opened, then the sealed chamber was opened and evacuated for another 10–15 min before transferring the sample to the analysis chamber. The data were collected at room temperature using non-monochromatic Al Kα (1486.6 eV) X-ray source operating at 400 W (15 kV and 27 mA). Data collection proceeded when the pressure in the analysis chamber reached ≈2×10−9 Torr. Survey spectra (0–900 eV at an electron takeoff angle of 45°) were collected at analyzer pass energy of 89.45 eV with energy resolution of 1.34 eV, 0.5 eV/step and an integration interval of 50 ms/step. The survey spectra consist of the average of 20 cycles with total acquisition time of 30.42 min. Multiplex spectra were collected at analyzer pass energy of 35.75 eV with energy resolution of 0.54 eV, 0.2 eV/step and an integration interval of 50 ms/step. The binding energies for the pristine (bare and coated) electrodes are reported as measured since there was no indication of electrode charging as indicated by the binding energy of the C 1s line for carbon black at 284.4 eV, which is in agreement with a number of previously reported results. 29,30 The cycled electrodes displayed a small degree of charging in the range of 0.2–0.4 eV, but their binding energies are reported with respect to carbon black at 284.4 eV. The binding energies of reference compounds in powder form are reported with respect to hydrocarbon at 285.0 eV. These procedures yielded the same binding energies for the C 1s and F 1s lines for powder PVDF and an electrode, which consisted of a mixture of PVDF and carbon black.

Depth profile analyses were made using 4 keV Ar ions with a raster size of 4×4 mm2. The sputtering was made in 0.5 or 1 minute intervals for a total sputtering time of 6 minutes. The C 1s, O 1s, F 1s, Li 1s, Co 2p, P 2p and Cl 2p photoemission lines were collected after each interval of sputtering at analyzer pass energy of 35.75 eV and an energy increment of 0.2 eV. The sputtering rate was calibrated using a 100 Å SiO2 film on a Si substrate and was found to be in the range of 25–30 Å of SiO2 per minute.

Another set of XPS spectra were collected on beamline X24A of the National Synchrotron Light Source utilizing monochromatic X-rays with energy of 2555 eV compared to 1486.6 eV for Al Kα X-rays in order to increase the depth of the analyzed region. The experimental setup consisted of a 2-stage high vacuum chamber with base pressure below 10−7 Torr and a Scienta R4000 detector running in transmission mode at pass energy of 200 eV with 0.3 mm analyzer aperture. The pass energy and aperture combination gives a resolution of about 0.29 eV at beam energy of 2139 eV as measured by the width of the Ag Fermi foot; though it will change with energy. The spectra were collected at an electron takeoff angle (between surface and detector) of 85°. The angle between the beam axis and the detector is 90°.

The sampling depth, defined as three times the electron mean free path, of C 1s, O 1s and F 1s photoelectrons generated by Al X-rays (1486.6 eV) at an electron takeoff angle of 90° relative to the plane of the sample (SDqθ) are 8.7, 7.3 and 6.3 nm, respectively. 19 Note that (1) the sampling depth at an electron takeoff angle of θ (SDqθ) is equal to SDqθ sin(θ) and (2) the sampling depth is proportional to (E)α where E is the kinetic energy of the photoelectrons and the exponent m for many elements and compounds is very close to 0.77. 32,33 Hence, the sampling depth of Li 1s, C 1s, O 1s, F 1s, P 2p and Co 2p photoelectrons generated with Al X-rays at an electron takeoff angle of 45° are estimated to be 7.9, 6.1, 5.2, 4.5, 6.7 and 4.1 nm, respectively.

On the other hand, the sampling depth of Li 1s, C 1s, O 1s, F 1s, P 2p and Co 2p photoelectrons for the synchrotron X-rays with excitation energy of 2555 eV at an electron takeoff angle of 85° are 15.2, 14.1 12.9, 12.2, 14.9, and 11.7 nm, respectively.

Results and Discussion

Electrochemical performance.— The “AlPO4” coating was found to improve the voltage efficiency and capacity retention when using LiPF6 electrolyte, but was detrimental when cycled in the LiClO4 electrolyte. As shown previously, the galvanostatic voltage profiles of lithium cells having bare and “AlPO4”-coated LiCoO2 electrodes revealed that the coated electrode exhibits higher capacity retention in comparison to the bare electrode upon cycling in 1 M of LiPF6 or EC-DMC between 2.5–4.7 V vs. Li+/Li with 4 hours hold at 4.7 V. 27 The galvanostatic voltage profiles of lithium cells having bare and “AlPO4”-coated LiCoO2 electrodes cycled in LiPF6 or LiClO4 between voltage limits of 2.0–4.6 V vs. Li+/Li with 4 h hold at 4.6 V are shown in Figure 1. Clearly, the coating as well as the type of salt used during cycling has a significant effect on the degree of capacity retention and the degree of polarization. Variations

![Figure 1](https://example.com/figure1.png)
in discharge capacity (mAh/g), discharge energy (Wh/kg) and energy efficiency (percent of discharge energy to charge energy) with cycle number are shown in Figure S1. The coated electrode cycled in LiPF6 has the highest capacity retention. It is interesting to note that the bare electrode cycled LiClO4 has higher capacity retention than the bare electrode cycled LiPF6 or the coated electrode cycled LiClO4. Hence, the coating doesn't provide an advantage when cycling was performed in LiClO4 electrolyte. The advantages of the “AlPO4” coating are more dramatic when one examines the discharge energy and energy efficiency (Figure S1). The discharge energy and energy efficiency for the 20th cycle decreased in the following order: coated electrode cycled in LiPF6 (~770 Wh/kg, ~90%), bare electrode cycled in LiClO4 (~750 Wh/kg, ~63%), coated electrode cycled in LiClO4 (~300 Wh/kg, ~56%), and bare electrode cycled in LiPF6 (~300 Wh/kg, ~54%).

It is known that structural instability can occur when LiCoO2 is cycled to high cutoff voltages (~4.2 V) and can cause degradation in battery performance and capacity retention. Previously, based on synchrotron X-ray diffraction data, we were able to show that the “AlPO4” coating prevented any structural instability, even when cycling in LiPF6 electrolyte to 4.7 V. Therefore, we are attributing the observed reduction in capacity retention to surface chemical changes and not to lattice instability when comparing the coated electrode cycled in LiPF6 versus the coated electrode cycled in LiClO4.

Scanning electron or transmission electron microscopy micrographs of the cycled active material to look for cracks or degradation of the primary particles of LiCoO2 were not taken. Though we believe a mechanical degradation study to be of interest, our extensive literature search suggested that LiClO4 is commonly used as a model electrolyte salt because it does not mechanically damage the active particles. A study by Ozawa, Yazami, and Fultz indicated that LiClO4 caused some measure of lithium re-intercalation, but no mechanical damage, when the cathode material was thermally aged for several weeks. Aurbach et al. found that Fe dissolution in LiClO4 was negligible even at elevated temperatures due to the lack of acidic contaminants and that Co dissolution occurred in LiPF6 based electrolytes. Hereafter, we describe the surface chemical changes evolved after cycling in LiClO4 and LiPF6 as determined by XPS.

XPS/Surface chemistry.— All cycled electrodes were examined in the discharged state. A comparison of survey spectra of various electrodes is shown in Figure S2. The C 1s, O 1s, Co 2p and F 1s spectra are shown in Figures 2–5, respectively. The Li 1s, P 2p, Cl 2p and Al 2p spectra are shown in Figures S3–S6, respectively. The concentrations based on these spectra are provided in Table I. The compositions of the near surface region for the pristine bare and coated electrodes are dominated by carbon, fluorine and then oxygen. The binding energy, full width-at-half-maximum (FWHM) and concentrations (in atomic percent) of various elements for each proposed chemical state are summarized in Table SI. The depth profile spectra of the O 1s, Co 2p, C 1s and F 1s regions are shown in Figures S7–S10, respectively, with concentrations based on these spectra are shown in Figure S11. Hereafter, we discuss the results for each element and correlate surface chemistry with electrochemical performance characteristics.

C 1s region.— The surface film developed in coated electrodes were found to be thicker with more oxygenated nature compared to that developed in bare electrode in both electrolytes based on the changes in C 1s intensity and binding energy. The C 1s photoemission spectra of pristine bare (Figure 2a) and pristine coated (Figure 2d) electrodes are dominated by the contributions from carbon black and PVDF. Various carbon chemistries are highlighted by
Figure 3. XPS spectra of the O 1s photoemission line for (a) pristine, bare LiCoO$_2$, (b) bare LiCoO$_2$ cycled in LiClO$_4$, (c) bare LiCoO$_2$ cycled in LiPF$_6$, (d) pristine, “AlPO$_4$”-coated LiCoO$_2$, (e) coated LiCoO$_2$ cycled in LiClO$_4$, and (f) coated LiCoO$_2$ cycled in LiPF$_6$. The dashed vertical lines represent binding energy values for lattice oxygen (LiCoO$_2$ lattice oxygen), oxygen present in lithium carbonate (Li$_2$CO$_3$), oxygen doubly bound to carbon in a carboxylic acid arrangement (O–C=O$^*$), oxygen bound to phosphorus (O–P(OR)$_3$), oxygen singly bound to carbon in a carboxylic acid arrangement (O–C=O), and oxygen in a fluorine based compound from LiPF$_6$ degradation (Li$_x$PF$_y$O$_z$). It should be noted that the y-axis is the same for all spectra but were shifted vertically for clarity.

Figure 4. XPS spectra of the Co 2p photoemission line for (a) pristine, bare LiCoO$_2$, (b) bare LiCoO$_2$ cycled in LiClO$_4$ (where the signal is multiplied by 5 for ease of viewing), (c) bare LiCoO$_2$ cycled in LiPF$_6$ (where the signal is multiplied by 5 for ease of viewing), (d) pristine, “AlPO$_4$”-coated LiCoO$_2$, (e) coated LiCoO$_2$ cycled in LiClO$_4$, and (f) coated LiCoO$_2$ cycled in LiPF$_6$. The dashed vertical lines represent binding energy values for lattice cobalt (LiCoO$_2$ 2p$_{3/2}$ and 2p$_{1/2}$), cobalt fluoride (CoF$_2$) and the Co 2p$_{1/2}$ satellite shake-up (Shake-up). It should be noted that the y-axis is the same for all spectra but were shifted vertically for clarity. However, the spectra for the bare electrode cycled in LiClO$_4$ (b) and in LiPF$_6$ (c) were scaled by a factor of 5.
the dashed lines (Figure 2) as follows: carbon black (284.4 eV), hydrocarbon (285.0 eV), C-H2CF2 (285.9 eV), C-O (∼286.5), C=O or O-C=O (∼288 eV), O-C≡O (∼289 eV), ROCO2Li or Li2CO3 (∼290.2 eV), CH2C=O (290.6 eV), and -CF3 (∼293.5 eV). As previously described, reference spectra of Super P carbon black, PVDF, and a composite electrode of 50 wt% PVDF and 50 wt% Super P carbon black were used as a guide to deconvolute the spectra of pristine composite electrodes. This procedure resulted in satisfactory fits for all of the cycled electrodes, except for the coated electrode cycled in LiClO4. In this case, the binding energies for all components were constrained to the reference electrode values. The additional small sub-peaks for the cycled electrodes relative to the pristine electrodes, which can be assigned to -CH2-CF2- chemistry. This sub-peak contribution is relatively small for all electrodes, though the bare and coated electrodes cycled in LiClO4 are at a higher binding energy (∼288.8 eV) which can be attributed to a carbon doubly bound to oxygen or singly bound to two oxygen atoms, or to fluorinated alkyl carbonate (R-CF2-C=O-CO2Li). The third sub-peak at ∼293.1 eV is assigned to the carboxylic chemistry. The final sub-peak at ∼293.1 eV is assigned to C-O chemistries. This sub-peak contribution is relatively weak for all electrodes, though the bare and coated electrodes cycled in LiClO4 are at a higher binding energy (∼288.8 eV), which can be attributed to a carboxylic chemistry. Table I. Summary of elemental concentrations (in atomic percent) as determined from XPS multiplex spectra.

<table>
<thead>
<tr>
<th>Sample</th>
<th>At. % Li</th>
<th>At. % C</th>
<th>At. % O</th>
<th>At. % F</th>
<th>At. % Co</th>
<th>At. % Al</th>
<th>At. % P</th>
<th>At. % Cl</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bare pristine</td>
<td>2.0</td>
<td>68.1</td>
<td>8.4</td>
<td>19.1</td>
<td>2.3</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Coated pristine</td>
<td>2.2</td>
<td>65.7</td>
<td>7.2</td>
<td>22.5</td>
<td>1.0</td>
<td>0.8</td>
<td>0.6</td>
<td>N/A</td>
</tr>
<tr>
<td>Bare LiPF6</td>
<td>24.9</td>
<td>11.1</td>
<td>12.9</td>
<td>43.8</td>
<td>0.6</td>
<td>1.7</td>
<td>5.1</td>
<td>N/A</td>
</tr>
<tr>
<td>Coated LiPF6</td>
<td>26.4</td>
<td>17.2</td>
<td>12.8</td>
<td>36.9</td>
<td>2.4</td>
<td>0.5</td>
<td>3.9</td>
<td>0.3</td>
</tr>
<tr>
<td>Bare LiClO4</td>
<td>0.0</td>
<td>43.7</td>
<td>31.3</td>
<td>16.1</td>
<td>3.9</td>
<td>4.7</td>
<td>N/A</td>
<td>0.3</td>
</tr>
<tr>
<td>Coated LiClO4</td>
<td>0.0</td>
<td>30.8</td>
<td>41.3</td>
<td>12.2</td>
<td>4.8</td>
<td>9.3</td>
<td>1.2</td>
<td>0.5</td>
</tr>
</tbody>
</table>
LiClO₄ have larger contributions, suggesting a reaction involving the PVDF binder. The above assignments are supported with assignments from the other XPS regions in the forthcoming discussions.

A relative estimate for the thickness of the surface films can be made based on the reduction of the C 1s intensity for carbon black in the cycled electrodes relative to that in the pristine electrodes. It is well known that a thin over layer with a uniform thickness will attenuate the intensity of the photoelectrons from the underlayer following the relationship

$$I/I₀ = e^{-d/Xc*sinθ}$$

where $d$ is the thickness of the over layer, $X_c$ is the mean free path of the photoelectrons, and $θ$ is the electron takeoff angle relative to the plane of the sample which is 45° in this experiment with Al X-rays.²⁶,⁴⁰ For C 1s photoelectrons using Al X-rays, $X_c$ is about 2.9 nm and, hence, the overlayer film thicknesses are estimated to be about 4.2 and 1.6 nm for the bare electrode cycled in LiPF₆ and LiClO₄, respectively, and are 5.3 and 4.4 nm for the coated electrode cycled in LiPF₆ and LiClO₄, respectively. It should be noted, and stressed, that a uniform thickness or composition may not be the case for the cycled electrodes. Therefore, these estimates are a crude measure for film thickness and may be compared on a relative basis. It should also be noted that XPS measurements provide a non-destructive means of measuring the film thickness without interfering with the chemical integrity of the film.

**O 1s region.**—The O 1s photoemission spectra for the pristine bare (Figure 3a) and coated (Figure 3d) electrodes display prominent contributions from LiCoO₂, lattice oxygen (O\(^{2-}\)), surface oxygen (O\(^-\)), and LiPO\(_4\) at 531.5 eV based on our reference (in the case of the coated electrode) in good agreement with previously reported results.²⁷,²⁵ The lattice oxygen at ≈529.5 eV, the surface oxygen species O-C = O and Li₂CO₃ collectively at ≈532.1 eV, the O(P)OR\(_3\) and O-C = O at species at ≈533.5 eV and LiPF₆O\(_4\) at ≈534.6 eV are identified by the dashed lines (Figure 3).

The sub-peak at 529.8 eV for the bare electrode cycled in LiPF₆ is close to that observed for our Co(OH)\(_2\) reference at 530.1 eV indicating that surface Co is present in the form of Co(OH)\(_2\) in agreement with the assignment based on the Co 2p region. On the other hand, the sub-peak at 529.9 eV for the bare electrode cycled in LiClO₄ is similar to that observed for our CoO reference at 529.9 eV indicating that surface Co is present in the form of CoO in agreement with the assignment based on the Co 2p region. The differentiation between Co(OH)\(_2\) and CoO was based mainly on the Co 2p region as will be discussed later in the text. The sub-peak at 529.2 eV for the coated electrode cycled in LiPF₆ cannot be attributed to LiCoO₂, CoO or Co(OH)\(_2\) as the Co 2p region confirmed the absence of these phases. Recent work by the Edström group⁵¹ has indicated a binding energy of 530.3 eV is indicative of Li₂SiO₄ and work by Ramana et al. assigns a binding energy of 530.1 eV to LiMnO₄⁴³ and 530.9 eV to LiFe₂P₂O₁₀.⁴⁴ Early work by Morgan et al. suggests a variety of pyrophosphates result in a binding energy of approximately 530.2 eV.⁴⁵ Clearly the literature indicates that this sub-peak is associated with oxygen as a polyanion. It is to be noted that such a low binding energy component is absent in the case of the coated electrode cycled in LiClO₄.

The O1s component located between 531.6 – 532.2 eV can be attributed to the surface oxygen of LiCoO₂ and oxygen in Li₂CO₃. Contributions at ≈531.6 eV (pristine bare electrode) and ≈531.9 eV (pristine coated electrode) are significantly reduced upon cycling in LiPF₆. This contribution, however, is significantly increased upon cycling the bare electrode in LiClO₄ but is absent in the case of the coated electrode cycled in LiClO₄. The binding energy of this component increased upon cycling from 531.6 to 531.9 eV (bare electrode in LiPF₆), 531.6 to 532.1 eV (bare electrode in LiClO₄), and 531.9 to 532.2 eV (coated electrode in LiPF₆) indicating that this subpeak is dominated by contributions from carbonate chemistry and/or oxygen doubly bonded to carbon (C = O) upon cycling. The subpeak at ≈533.7 eV, which can be associated with oxygen singly bound to carbon (RO*-CO-O*R) in carbonate, emerged at a moderate level upon cycling bare and coated electrodes in LiPF₆ and bare electrode in LiClO₄, which has the highest contribution of this component.

The high binding energy sub-peak at ≈535.5 eV, seen in the pristine bare electrode, the bare electrode cycled in LiClO₄, and the bare electrode cycled in LiPF₆, was not observed in any of our reference compounds. This sub-peak has been reported to be the result of carbonate impurities on the surface of the LiCoO₂ particles.⁴⁶ This contribution emerged at significant levels upon cycling bare electrodes in LiPF₆ and LiClO₄. A weak contribution (≈1 atomic %) with a slightly lower binding energy (535.1 eV) was observed for the coated electrode cycled in LiPF₆. Also, a sub-peak is observed at ≈536.4 eV for the bare electrode cycled in LiClO₄ and a sub-peak is observed at ≈535.8 eV for the coated electrode cycled in LiClO₄, which were not present in any of the reference materials we used for calibration purposes. For the coated electrode cycled in LiClO₄, a unique sub-peak at ≈532.9 eV emerged, which can be related to oxygen doubly bound to carbon. Another unique sub-peak at 534.5 eV also emerged, which can be related to oxygen singly bound to carbon. Due to the observed high binding energies, these components are thought to be the result of differential charging as a result of low electrical conductivity of the electrode sample after cycling. This further complicates not only the O 1s assignments and differentiation of the peaks associated with LiPF₆O₄ and alkyl carbonates, but the C 1s assignments as well and can only be speculated currently.

The lack of a contribution from the LiCoO₂ lattice oxygen sub-peak for the bare electrode cycled in LiPF₆ in this study, which was not the case in our previous study,²⁷ indicates that the surface film being formed is thicker in the current investigation. The formation of a thicker film could be the result of cycling between 2.0–4.6 V in the current investigation versus 2.5–4.7 V in the previous investigation, as the electrolyte is more likely to break down while discharging to 2.0 V. As previously reported for the coated electrode cycled in LiPF₆, the oxygen species were considered to be associated with the formation of Co-Al-O-F and PF₆(OH)₂ species. On the other hand, the oxygen species for the bare electrode cycled in LiPF₆ included significant contributions from lattice oxygen, Li₂CO₃, O-C≡O, and LiPF₆O₄. As will be discussed later, based on the binding energy of the CI 2p line and its concentration, none of the oxygen signal for the electrodes cycled in LiClO₄ can be attributed to the salt. The electrodes cycled in LiClO₄ have contributions from higher binding energy sub-peaks. This would suggest that the salt is decomposing and reacting with the solvent material, forming insoluble reaction products that are on the surface of the electrode or become part of the surface film. The bare electrode cycled in LiPF₆ has a larger contribution from the sub-peak at ≈535.4 eV, which is considered to play a role in the performance profile. The coated electrode cycled in LiClO₄ has the highest concentration of high binding energy oxygen chemistries, indicating a thicker resistive surface film that is forming on the surface and accounting for the poor electrochemical performance.

The presence of the higher binding energy sub-peaks in the O 1s region at ≈536 eV observed for the electrodes cycled in LiClO₄ could indicate the formation of ether-based solid products, which result from the breakdown of the electrolyte.⁴⁷-⁵⁰ These species are resistive as illustrated by the differential charging observed in the hard X-ray data, which will be discussed later in the text. The large contribution of the oxygen sub-peak at 535.5 eV for the bare electrode cycled in LiPF₆ compared to the coated electrode cycled in LiPF₆ suggests oxygen interaction with fluorine, possibly as suggested by Veith et al.,⁵¹ but certainly the formation of more covalent and/or polymeric material than in the case of the coated electrode.⁴⁸-⁵⁰

**Co 2p region.**—Cobalt fluoride was found to dominate the cobalt chemistry in coated electrodes cycled in both electrolytes but not in bare electrodes. The Co 2p spectra for the pristine bare (Figure 4a) and coated (Figure 4d) electrodes, with the Co 2p\(_{3/2}\) peak at ≈780 eV and the satellite at approximately +10 eV, are characteristic of LiCoO₂ and LiAlCo\(_{y}\)O\(_{2}\), respectively. The cobalt signal for the bare electrode cycled in LiPF₆ at 779.8 eV is very weak and, therefore, resulting in a poorly developed satellite structure at ≈+6.1 eV.
These values compare well with our values for Co(OH)2 (Co 2p3/2 at 779.8 eV) with a satellite structure at 6.1 eV higher indicating that the major portion of surface Co is present in the form of Co(OH)2. The Co(OH)2 chemistry is also supported by results based on the O 1s region. For the bare electrode cycled in LiClO4, the Co 2p3/2 line has a binding energy of 780.3 eV with a satellite structure at approximately +7 eV. These values compare well to our values for the CoO reference (Co 2p3/2 at 780.0 eV and satellite contribution at +7 eV) indicating that a large portion of surface Co is present in the form of CoO. This assignment is also supported by results based on the O 1s region. However, the presence of a modest amount of CoF2 and/or oxyfluoride cannot be ruled out as the peak is slightly shifted to higher binding energy relative to that for CoO. The presence of the CoF2 and/or oxyfluoride is confirmed based on synchrotron XPS data as will be demonstrated later in the text. The spectrum for the coated electrode cycled in LiPF6 with the 2p3/2 peak at ≈783.7 eV and a satellite separation of ≈4.5 eV is consistent with the reference spectrum of CoF2 indicating the formation of cobalt fluoride in agreement with previous results.27 The spectrum for the coated electrode cycled in LiClO4 with a Co 2p3/2 sub-peak at ≈783.9 eV also indicates the formation of CoF2.

The Co concentrations for the electrodes cycled in LiClO4 are higher than those for the electrodes cycled in LiPF6 (Table S1). It is noted that the sampling depth for the Co 2p electrons is 4.1 nm, which is smaller than or comparable to the overlayer film thickness as determined based on the C 1s region except in the case of the bare electrode cycled in LiClO4 where it is greater than the overlayer thickness. Hence, the Co signal is from Co residing in the overlayer film except in the case of the bare electrode cycled in LiClO4 where the Co signal can have an additional contribution from Co residing below the overlayer film. Therefore, Co dissolution may occur more frequently in LiClO4 cycled electrodes, which then results in Co products being deposited in the overlayer film.3

As reported previously,27 the formation of CoF2 in the case of the LiPF6 electrolyte can be due to a reaction between LiCoO2/Al2O3 and/or LiCoO2 with HF present as an impurity in the electrolyte. However, in the case of the LiClO4 electrolyte, the only source of F is the PVDF binder, which can produce HF as a result of a dehydrofluorination reaction as reported previously.25,26 The reaction mechanism, therefore, could be similar for both the LiPF6 and LiClO4 electrolytes but the source of HF is different. In one case, it is the HF impurity in LiPF6 and, in the other case, dehydrofluorination of the PVDF binder.

F 1s region.— The F 1s spectra from the pristine electrodes (Figures 5a and 5d) display mainly a single peak at ≈687.8 eV, which corresponds to fluorine chemistry from PVDF. A weak component with binding energy of ≈685 eV is also observed and can be related to the presence of LiF. The origin of LiF was attributed previously to a dehydrofluorination reaction of PVDF generating HF, which then reacts with LiCoO2 or Li2CO3 present on the surfaces of the LiCoO2 particles to form LiF.25 Upon cycling the bare electrode in LiPF6, the majority of the F signal arises from species at 687.9 eV, associated with PVDF, LiPF6 and its degradation products. However, a high binding energy peak (≈690.9 eV) is also present. This high binding energy was reported in recent Li-air work and was assigned to highly ionic species formed with the addition of organic groups promoted by organo-lithium.47 The high binding energy species, however, could also be the result of highly resistive species that is experiencing differential charging. For the coated electrode cycled in LiPF6, a single broad peak is observed at ≈688.0 eV, which is assigned to PVDF, LiPF6 and its degradation products. For the LiClO4-cycled electrodes, the fluorine contribution was limited to PVDF and the relative intensity of the F 1s signal reflects this (the signal in Figure 5 is multiplied by 5 for clarity). For both the bare and coated electrodes cycled in LiClO4, the F 1s region consists of a major contribution with binding energy of ≈688.0 eV, which can be associated with PVDF and AlF3 (with F 1s binding energy of 687.4 eV from our AlF3 reference). Al comes from the current collector in the case of the bare electrode, but also from the coating in the case of the coated electrode. For the bare electrode cycled in LiClO4, a component with binding energy at 685.3 eV, which can be related to LiF, and a high binding energy component at 689.6 eV, which could be associated with a highly ionic species within organic material as mentioned previously or differential charging, were also present.

Based on our CoF2 reference, a subpeak which corresponds to the CoF2 chemistry is expected at ≈686.0 eV in the F 1s region. However, due to the relatively large concentration of F from PVDF as well as LiPF6 and its degradation products in the case of coated electrode cycled in LiPF6, the subpeak associated with CoF2 chemistry is not clearly resolvable. However, the assignment for the CoF2 chemistry was clearly confirmed based on the Co 2p photoemission region as discussed earlier.

Al 2p region.— The Al 2p spectrum for the pristine coated electrode (Figure S6) displays a peak at ≈73.7 eV that is associated with AlLiCoO2/Al2O3, while that for the coated electrode cycled in LiPF6 displays a peak at ≈76.4 eV that is associated with AlF-O and/or AlF3 species. As expected, no Al contribution is observed for the pristine bare electrode. The Al 2p spectrum for the bare electrode cycled in LiPF6 consists of a single peak at 76.9 eV, which is associated with Al-F-O and/or AlF3 from the interaction of the current collector with the LiPF6 electrolyte and/or PVDF. The Al spectrum for the bare electrode cycled in LiClO4 consists of two sub-peaks at 76.1 eV and 78.2 eV, which can be associated with Al-F-O and/or AlF3. The Al 2p spectrum for the coated electrode cycled in LiClO4, however, consists of a relatively large intensity sub-peak at ≈77.4 eV that is considered to be associated with AlF3 and/or an Al-F-O oxyfluorides chemistry. The higher binding energies observed for the bare electrode cycled in LiPF6 and LiClO4 relative to that observed for our AlF3 reference (76.7 eV) suggest a resistive film that is differentially charging. It should be noted that the atomic concentrations for aluminum are significantly higher for the LiClO4 cycled electrodes than for the LiPF6 cycled electrodes and the pristine electrodes. Therefore, since the LiClO4 cycled electrodes surfaces have no visible spots from the current collector, which could contribute to the Al spectrum, the origin of the Al signal would be due to Al dissolution and re-deposition onto/into the cathode surface during cycling, as aluminum is known to be subject to corrosion under high potentials and electrolyte compositions.31-33 This could be due to the detachment of the active material at the current collector interface and the subsequent Al dissolution into the electrolyte and its re-deposition on the electrode surface. Similar corrosion products of the Al current collector were reported to occur after cycling in LiPF6 in PC:DEC and EC:DMC electrolytes.51

Synchrotron based XPS.— In an effort to examine the depth distribution of the respective surface films and the thickness of the metal fluoride phases, the electrodes were also inspected using monochromatic synchrotron X-rays with energy of 2555 eV. The O 1s photoemission spectra (Figure S12) are similar to spectra obtained using our conventional in-house spectrometer (Figure 3) with one very noticeable exception. Only electrodes cycled in LiClO4 exhibit intense high binding energy peaks beyond 536 eV. The F 1s spectra (Figure S13) are also similar to the in-house spectra (Figure 5), except for the high binding energy peaks (~693 eV), which appeared in electrodes cycled in LiClO4. High binding energy peaks were also observed in the Al 2p and Al 2s spectra (not shown) and were all shifted by similar amount as those of the F and O high binding energy peaks. We believe that these high binding energy peaks associated with O, F and Al are the result of differential charging. Thus, the highly resistive species appear to contain Al, O, and F. Clearly, the films formed on the surfaces of the electrodes cycled in LiClO4 are more resistive in nature than the films formed on the surfaces of the electrodes cycled in LiPF6, regardless of the coating. Therefore, we speculate that these species could be due to dissolution of the Al current collector and its redeposition onto/into the electrode surface. Differential charging occurs less frequently with spectrometers employing conventional nonmonochromatic Al or Mg X-rays relative to spectrometers employing monochromatic synchrotron radiation. In the case of conventional spectrometers, the secondary electrons,
generated by the X-rays passing through the window of the source, tend to neutralize the sample surface.

Synchrotron based XPS helps to reveal the thickness of the CoF₂ formed in the coated electrode cycled in LiPF₆. The Co 2p spectrum (Figure S14) for the bare LiCoO₂ electrode cycled in LiPF₆ is consistent with conventional data showing no contribution from CoF₂. The Co 2p spectrum for the bare electrode cycled in LiClO₄ displays contributions from lattice LiCoO₂ as well as CoF₂. However, the Co 2p spectrum for the coated LiCoO₂ electrode cycled in LiPF₆ displays a contribution from LiCoO₂ in addition to the CoF₂ contribution. Since CoF₂ is the only chemistry observed in the case of conventional data, it suggests the depth of the region that contains CoF₂ for the coated LiCoO₂ electrode cycled in LiPF₆ to be greater than 4 but less than 11 nm. The formation of CoF₂ also occurs in the case of the electrodes cycled in LiClO₄ as the surface doesn’t contain enough chlorine to account for all of the highly oxidized Co. The extent of the formation of CoF₂ is greater in the case of the coated LiCoO₂ electrode cycled in LiClO₄ relative to the bare electrode cycled in LiClO₄. The CoF₂ peak was also observed in conventional data for both the bare and coated LiCoO₂ electrodes cycled in LiClO₄ and cannot be attributed to differential charging. In this case, the formation of CoF₂ suggests an interaction with the PVDF binder since it is the only source of F. Such an interaction could lead to degradation of PVDF and the loss of electrical connectivity between particles and be responsible for the poor performance.

Conclusions

Our previous work based on high resolution synchrotron X-ray diffraction data,2 showed that the addition of the “AlPO₄”-coating prevented lattice instability when cycling in LiPF₆ electrolyte even at higher voltages (4.7 V). Based on surface analysis by XPS and the XRD results, we proposed that the coating offers protection against corrosion by HF, in addition to lattice stability of the coated LiCoO₂ in the cathode. Based on voltage-capacity profiles in Figure 1, the observed trends in discharge energy and energy efficiency after 20 cycles are as follows: “AlPO₄”-coated electrode in LiPF₆ (∼770 Wh/kg, ∼90%), bare electrode cycled in LiClO₄ (∼500 Wh/kg, ∼63%), “AlPO₄”-coated electrode cycled in LiClO₄ (∼300 Wh/kg, 56%), bare electrode cycled in LiPF₆ (∼300 Wh/kg, ∼54%). Chemical analysis via XPS in the current investigation revealed several interesting results. The electrodes cycled in LiClO₄ showed CoF₂ formation in the Co 2p photoemission region (Figure 4). The only source of fluorine for these electrodes is the PVDF binder, suggesting dehydrofluorination or leaching of the F from the material. Also, Al was detected in the surface films for the bare electrodes. The Al concentrations are significantly higher for the electrodes cycled in the LiClO₄ electrolyte. This suggests that there is corrosion of the current collector and then redeposition from the electrolyte onto the surface film. The corrosion of the current collector has been shown previously,51–53 but the degree of corrosion and exactly what variable has caused the corrosion is currently unclear. An estimation of the film thickness was made based on attenuation of the carbon black intensity for the cycled electrodes relative to that of the corresponding pristine electrodes. Sputter depth profiling with energetic Ar-ions (4 keV) provided some information (Figures S7–S10), but information from the C 1s region is of limited use as the bombardment of carbon films is known to cause some chemical changes to the carbon morphologies.54,55 Additionally, differential charging observed in the synchrotron-based XPS studies support the electrolytically resistive nature of the Al oxfluoride (Al-O-F) formed during cycling in the LiClO₄ electrolyte.

The “AlPO₄” coating was found to improve the voltage efficiency and capacity retention when using the LiPF₆ electrolyte, but was detrimental when using the LiClO₄ electrolyte. This indicates that the enhanced cycling performance with surface coating is only realized when cycling in LiPF₆, suggesting that while the coating material may prevent HF corrosion of the active material, the electrolyte composition also plays a key role in cell performance. XPS reveals that the “AlPO₄” coating promotes the formation of metal fluoride (e.g. CoF₂, and Al-O-F) in both electrolytes. The source of fluorine in the coated LiCoO₂ electrode cycled in LiPF₆ is largely attributed to the LiPF₆ salt whereas the source of fluorine in the coated LiCoO₂ electrode cycled in LiClO₄ is the binder PVDF. Furthermore, the data appear to indicate that the surface film formed on the bare electrodes is thinner than the surface film formed on the coated LiCoO₂ electrodes, with the film formed on the bare electrode cycled in LiClO₄ being the thinnest (∼1.6 nm) and the film formed on the coated LiCoO₂ electrode cycled in LiPF₆ being the thickest (∼5.3 nm). We stress that these are crude estimates based solely on the assumptions of a consistent photoelectron mean free path across chemistries and that these estimates are to aid the reader in addressing the questions of film thickness on a relative basis. Our study suggests that the working mechanism of “AlPO₄” coating is the formation of stable metal fluorides and/or Co/Al oxfluoride surface film via reactions between the surface coating and the F source from the electrolyte (e.g., HF impurity in the LiPF₆ electrolyte). When the F source from the electrolyte is removed such as in the case of LiClO₄, the coating no longer works positively, but appears to mainly extract the fluorine from the PVDF binder causing degradation of the electrode. The fluorine source from PVDF is likely to be also HF, as a result of dehydrofluorination reaction as discussed earlier in the text.25,26

Acknowledgment

This work was supported in part by the MRSEC Program of the National Science Foundation under award number DMR-0819762 and the Assistant Secretary for Energy Efficiency and Renewable Energy, Office of FreedomCAR and Vehicle Technologies of the U.S. Department of Energy under contract no. DE-AC03-76SF00098 with the Lawrence Berkeley National Laboratory. The synchrotron XPS experiment was conducted on beamline X24A at the National Synchrotron Light Source of Brookhaven National Laboratory, which is supported by the U.S. Department of Energy, Office of Basic Energy Sciences, under contract no. DE-AC02-98CH10886.

References
