Unraveling the Complex Delithiation Mechanisms of Olivine-Type Cathode Materials, $\text{LiFe}_x\text{Co}_{1-x}\text{PO}_4$


†Department of Chemistry, University of Cambridge, Lensfield Road, Cambridge, Cambridgeshire CB2 1EW, U.K.
‡X-ray Science Division, Advanced Photon Source, Argonne National Laboratory, Argonne, Illinois 60439, United States
§Department of Chemistry, State University of New York at Stony Brook, Stony Brook, New York 11794-3400, United States

ABSTRACT: The delithiation mechanisms occurring within the olivine-type class of cathode materials for Li-ion batteries have received considerable attention because of the good capacity retention at high rates for LiFePO$_4$. A comprehensive mechanistic study of the (de)lithiation reactions that occur when the substituted olivine-type cathode materials LiFe$_x$Co$_{1-x}$PO$_4$ ($x = 0.05, 0.125, 0.25, 0.5, 0.75, 0.875, 0.95, 1$) are electrochemically cycled is reported here using in situ X-ray diffraction (XRD) data and supporting ex situ $^{31}$P NMR spectra. On the first charge, two intermediate phases are observed and identified: $\text{Li}_{4-x}(\text{Fe}^{3+})_x(\text{Co}^{2+})_{1-x}\text{PO}_4$ for $0 < x < 1$ (i.e., after oxidation of Fe$^{2+}$ to Fe$^{3+}$) and $\text{Li}_{2/3}\text{Fe}_{x}\text{Co}_{1-x}\text{PO}_4$ for $0 \leq x \leq 0.5$ (i.e., the Co-majority materials). For the Fe-rich materials, we study how nonequilibrium, single-phase mechanisms that occur discretely in single particles, as observed for LiFePO$_4$ at high rates, are affected by Co substitution. In the Co-majority materials, a two-phase mechanism with a coherent interface is observed, as was seen in LiCoPO$_4$, and we discuss how it is manifested in the XRD patterns. We then compare the nonequilibrium, single-phase mechanism with the bulk single-phase and coherent interface two-phase mechanisms. Despite the apparent differences between these mechanisms, we discuss how they are related and interconverted as a function of Fe/Co substitution and the potential implications for the electrochemistry of this system.

1. INTRODUCTION

Since the initial publication by Padhi et al. in 1997 on LiFePO$_4$, the olivine family has been extensively researched as potential cathode materials for Li-ion batteries. LiFePO$_4$‘s high stability, long cycle life, good reversibility, and safe operating voltage (3.45 V vs Li$^+$/Li) have led to its use in commercial batteries. While LiFePO$_4$ has been widely studied, the mechanism by which it is transformed during electrochemical cycling is not trivial. The transformation mechanisms for the substituted and in principle higher-energy density variants LiFe$_x$M$_{1-x}$PO$_4$ (M = Mn, Co, Ni; $0 \leq x \leq 1$) have not been more complex and generally not well understood. Understanding how Li is deintercalated and reintercalated upon charging and discharging, respectively, is fundamental to explaining the electrochemical properties of known electrode materials and essential to help develop new electrode materials. Specifically, substitution of Mn, Co, and Ni generally results in poorer performance in terms of rate and capacity, but this is not true of all levels of metal substitution. It is therefore important to understand why some compositions show improved performance and others do not.

Here we use time-resolved in situ synchrotron X-ray diffraction methods to explore systematically how Co substitution in LiFePO$_4$ alters the structural transformations that occur upon cycling for the entire LiFe$_x$Co$_{1-x}$PO$_4$ phase diagram. We start by describing the possible relevant (de)lithiation mechanisms proposed for LiFe$_x$M$_{1-x}$PO$_4$ and how they are, or would be, manifested in the X-ray diffraction (XRD) data (Figure 1) in order to help in the interpretation of the in situ XRD data for the LiFe$_x$Co$_{1-x}$PO$_4$ series presented in this paper.

Initially, XRD and transmission electron microscopy (TEM) studies carried out on micron-sized LiFePO$_4$ particles identified a two-phase reaction mechanism (A) (illustrated in Figure 1) in which both end-member phases (LiFePO$_4$ and FePO$_4$) are present, separated by a coherent interface within a single particle, at intermediate states of charge. This mechanism is observed as the simultaneous disappearance and growth of the XRD reflections of the reactant and product phases, respectively. Although micron-sized particles can be chemically delithiated, their electrochemical performance is poor. LiFePO$_4$ (space group $Pmn\alpha$) has one-dimensional Li diffusion channels in the $b$ direction, and its electrochemical performance was found to significantly improve when the particles were nanosized.

The decrease in particle size also leads to a change in the reaction mechanism since the high-energy interface between LiFePO$_4$ and FePO$_4$ is no longer stable within a single nanoparticle and only fully lithiated and fully delithiated particles could be detected in ex situ XRD studies upon cycling. These findings were explained by Delmas et al. in their domino-cascade model (B), in which the reaction occurs particle-by-particle (as shown in Figure 1), resulting in sequential, heterogeneous delithiation.

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of the particles in the electrode. It was proposed that the particles still undergo a two-phase mechanism, but since the interface is energetically unfavorable, it propagates very quickly within each particle. It should be noted that as a result of the added strain at the phase boundary that exists during reaction scheme A, the full widths at half-maximum of specific classes of reflections in the diffraction experiment are expected to be larger than if the two phases exist in different particles, such as in scheme B (as illustrated in Figure 1). Recent soft X-ray ptychography combined with X-ray absorption spectroscopy and TEM measurements have shown that LiFePO4 and FePO4 can coexist in particles as small as 100 nm.7

The good capacity retention at exceptionally high rates for LiFePO4 nanoparticles8 is in apparent contradiction with a two-phase mechanism: two-phase mechanisms typically result in high activation energy barriers for the nucleation and growth of a new phase. Although the Li solubility in LiFePO4 and Li1−yFePO4 increases as the particle size decreases, there is a still a miscibility gap even for 34 nm particles.7 Density functional theory calculations by Malik et al.10 predicted that a single-phase mechanism in which both phases coexist in a single particle; (B) the particle-by-particle reaction regime, where the particles exist only as either Li1 or Li0; (C) the bulk single-phase mechanism; (D) the nonequilibrium single-phase transformation occurring sequentially particle-by-particle; (E) the two-phase mechanism with a coherent interface, explored in more detail in this paper.

Figure 1. Simplified illustration of five different possible delithiation schemes for the olivine materials and their resulting in situ XRD responses for a single reflection (such as the 020 reflection) at the compositions Li1, Li1.5, and Li0 (i.e., LiMPO4, Li0.5MPO4 and MPO4); (A) the bulk two-phase mechanism in which both phases coexist in a single particle; (B) the particle-by-particle reaction regime, where the particles exist only as either Li1 or Li0; (C) the bulk single-phase mechanism; (D) the nonequilibrium single-phase transformation occurring sequentially particle-by-particle; (E) the two-phase mechanism with a coherent interface, explored in more detail in this paper.

within one particle.12,15 However, at lower charge rates, since the nanosized LiFePO4 particles react very quickly (a few particles at a time), the patterns from the two end-member phases dominate the XRD response, and the response is essentially indistinguishable from that seen for scheme B in Figure 1.16 The nonequilibrium single-phase mechanism (D) should be contrasted to that expected for a thermodynamically stable solid solution, where the peaks shift continuously from those of the fully lithiated to the fully delithiated phase (scheme C in Figure 1). If in scheme A (the bulk two-phase reaction) there is some coherency at the interface, there will be a distortion at the interface of the two phases to reduce the strain, leading to the final scheme, the coherent interface model (E). The subtle differences between schemes E and A and how they are manifested in the in situ powder XRD patterns of the nanoparticulate olivine materials will be discussed in detail in this paper.

Here, to explore the delithiation mechanisms occurring within the olivine class of cathode materials, we study the LiFeCoxPO4 series (x = 0, 0.05, 0.125, 0.25, 0.5, 0.75, 0.875, 0.95, 1). Complex in situ XRD patterns are generally observed for nanoparticulate cation-substituted olivine materials upon cycling, with both solid-solution and two-phase behavior at low cycle rates,14,17 suggesting that the mechanism of (de)lithiation deviates from those of the nonsubstituted materials. For example, in the Mn-substituted series LiFeMnx1−xPO4, an intermediate phase, LiFeMn1−xPO4, was observed in the in situ XRD patterns and exhibited a larger Li solubility than the end members, LiFeMn1−xPO4 and FeMn1−xPO4.14 A two-phase mechanism between LiFeMn1−xPO4 and LiFeMn1−xPO4 was observed upon charge, but a bulk single-phase transformation (mechanism C) between the two phases was then seen upon discharge. Substitution on the transition metal site in the olivine cathode materials is thought to facilitate the single-phase mechanism,17–19 helping to improve the rate performance of

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the cathode materials, as demonstrated in vanadium-substituted LiFePO₄.

Very different mechanisms are observed for the Co-containing olivines: Ehrenberg and co-workers observed by in situ XRD that the delithiation mechanism of the end member LiCoPO₄ occurs via a LiₓCoPO₄ intermediate with two distinct reactions occurring: LiCoPO₄ → LiₓCoPO₄ and LiₓCoPO₄ → CoₚPO₄. The processes result in significant loss of long-range order. In our previous study in situ XRD and ex situ NMR spectroscopy, we showed that the intermediate phase has the composition Liₓ/3(Co³⁺)₁/₃(Co²⁺)₂/₃PO₄, its structure being obtained by an (a × 3b × c) supercell expansion of the primitive olivine unit cell. Here we systematically monitor the changes in the in situ XRD patterns for high and low substitution levels of both Fe and Co and then analyze how these changes can be understood within the different delithiation reaction schemes (using Figure 1 as a guide). This allows us to develop a systematic understanding of how substitution affects the complex reaction mechanisms in this series.

We first present XRD characterization of the as-synthesized materials in the LiFeₓCo₁−ₓPO₄ series (section 3.1). We then consider Fe-rich LiFeₓCo₁−ₓPO₄ (x ≥ 0.875) and use whole-powder-pattern fitting as described by Liu et al. to study the first 1.5 cycles (section 3.2). We next study the highly substituted materials, LiFe₀.₅Co₀.₅PO₄ and LiFe₀.₂₅Co₀.₇₅PO₄, and identify the intermediates that are formed upon charging the cosubstituted olivines (section 3.3). Relevant NMR spectra are presented to confirm the bulk oxidation changes. Using XRD patterns, refinements, and simulations, we discuss in detail the nature of any coherent interfaces formed during a two-phase reaction and explain how they are manifested in the XRD patterns. We compare the delithiation mechanisms for the transformations between the starting, intermediate, and final phases as a function of Co content. We show that the relationships between the different mechanisms are determined by the length of the coherent interface, the ability of the material to tolerate intermediate Li compositions, the extent of disorder of Li/vacancies and Fe³⁺/Co²⁺, and the change in volume between the two end-member phases. From the study of the whole series, trends emerge that were not apparent when single compositions were investigated individually.

2. EXPERIMENTAL DETAILS

2.1. Solid-State Synthesis of LiFeₓCo₁−ₓPO₄. The carbon-coated series LiFeₓCo₁−ₓPO₄ (x = 1, 0.95, 0.875, 0.5, 0.25, 0.125, 0.05, 0) were synthesized via the solid-state method using iron oxalate (Sigma-Aldrich, 99.997%), cobalt oxalate (Sigma-Aldrich), lithium carbonate (Sigma-Aldrich, 99.997%), ammonium dihydrogen phosphate (Sigma-Aldrich, 99.999%), and 10 wt % Ketjen black (AkzoNobel) in stoichiometric mixtures. After high-energy ball milling for 20 min, each reaction mixture was pelletized and heated to 600 °C under flowing argon. For x = 1, 0.95, and 0.875, the precursors were heated for 6 h. For x = 0.75, they were heated for 6 h, cooled, and reheated for a further 11 h. For LiFe₀.₅Co₀.₅PO₄ (x = 0.5, 0.25, 0.125, 0.05, 0), the precursors were heated for 6 h and then cooled and reheated twice for 11 h before a final 24 h heating step. The additional heating and cooling steps were carried out to decrease the amount of impurities present in the final product.

2.2. Film Fabrication and Battery Assembly for the in Situ XRD Experiments. The electrode was prepared by grinding 85 wt % carbon-coated LiFeₓCo₁−ₓPO₄, 5 wt % Super P carbon (Alfa Aesar), 5 wt % carbon black (Vulcan XC-72, Cabot Corporation), and 5 wt % polytetrafluoroethylene (PTFE) (Sigma-Aldrich) in a mortar and pestle. The powder was pressed into a 13 mm diameter pellet with a thickness of ~150 μm and a mass of ~22 mg. The AMPiX cell was assembled in an argon-filled glovebox using Li metal as the counter electrode, a Whatman GF/B borosilicate microfilter as the separator, and a 1 M solution of LiPF₆ in a 1:1 mixture of ethylene carbonate/dimethyl carbonate as the electrolyte (Tomiyama Pure Chemical Industries).

2.3. In Situ XRD. In situ XRD experiments were performed at the powder diffraction beamline, 11-BM, at the Advanced Photon Source (APS) at Argonne National Laboratory (ANL) using a 12-channel analyzer detector array (λ = 0.41369 Å, beam size 1.5 mm × 0.5 mm). Data spanning a 2θ range of 0–26° were collected using a step size of 0.002°. To increase the experiment throughput, multiple batteries were assembled on a motorized stage and translated into the X-ray beam periodically for diffraction measurements. For x = 0.95, 0.875, 0.125, and 0.05, each measurement took 10 min 42 s (using a time per step of 0.34 s), and scans were obtained every 60 min 25 s. For x = 1, 0.75, 0.5, 0.25, and 0, more scans were acquired during parts of the electrochemical cycling where large structural changes had been observed to occur in earlier preliminary measurements on these samples. All of these scans took 7 min 40 s (the time per step was 0.23 s). Since the sampling of the electrochemical processes was nonuniform for these batteries, the points where scans were taken are shown in Figures S1 and S2 in the Supporting Information (S1) and in the main text (for the first charge) as indicated in the figure captions. All of the batteries for the in situ XRD experiments were galvanostatically cycled at a rate of C/20 using a Maccor model 4300 cycle. The current was continuously applied while the samples were automatically moved in and out of the beam on the sample stage, so that they did not have a chance to “relax.” A rate of C/20 was used for three reasons: (a) The scan time for one XRD pattern took 10 min 42 s (for x = 1, 0.75, 0.5, 0.25, and 0), which at a rate of C/20 corresponds to change in state of charge of <0.9%, which we thought was small enough to result in minimal peak broadening or other artifacts. (b) Since we were studying six cells simultaneously, with scans taking 10 min 42 s, if we cycled at C/20, we could collect on average ~20 data points on the charge. As these materials are known for having more than one plateau, we felt that it was important to collect as many data points as realistically possible. (c) We wanted all of the materials to reach highly charged states (i.e., to remove as much Li as possible), and since the Co-containing materials show poorer electrochemical than LiFePO₄ at higher rates, we chose a moderately low cycle rate. Rietveld refinements were performed using the Topas Academic software. The individual XRD patterns, Rietveld refinements, and difference plots for patterns from the in situ XRD data for LiFePO₄ during the first charge at 8%, 57%, and 99% state of charge are shown in Figure S3.

2.4. Whole-Powder-Pattern Fitting of the in Situ XRD Patterns. The same method as discussed in our earlier paper was used in this study. The background was described by the Chebyshev polynomial. The instrumental broadening was assumed to be negligible and was not considered in the refinement; hence, the broadening of the diffraction peak was attributed solely to the size and strain effects of the sample. A Lorentzian peak profile was used to model the size broadening, and the apparent size was assumed to be isotropic with respect to different hkl reflections. The dependence of the full width at half-maximum (fwhm), β, on θ is given by

$$\beta = \frac{\lambda}{L \cos \theta_{\text{half}}}$$

(1)

where λ is the wavelength and L is the refined apparent size parameter. The strain/compositional effect was described by a convolution of symmetrical and asymmetrical profile functions. A Gaussian profile peak function was chosen to model the symmetrical broadening due to strain, and this strain was also assumed to be isotropic with respect to different hkl reflections. The θ dependence of the fwhm is given by

$$\beta = E \tan \theta_{\text{half}}$$

(2)

where E is the refined symmetrical strain parameter. The asymmetrical profile was modeled using an exponential function:

$$f(\theta) = \exp \left( -\frac{2\theta - 2\theta_{\text{halfl}}}{e_{\text{as}}} \right)$$

(3)

where e_{as} is the refined parameter and θ is defined in the range [θ_{halfl} → +∞] for e_{as} > 0 and [−∞, θ_{halfl}] for e_{as} < 0. Because of the anisotropic changes...
in the lattice parameters going from LiFeCo$_1$PO$_4$ to Fe$_x$Co$_{(1-x)}$PO$_4$ where $a$ and $b$ contract and $c$ expands, we had to include an $hkl$-dependent description of the asymmetrical profile, which was done by including a symmetrized spherical harmonics series in $\varepsilon_m$:

$$\varepsilon_m = \sum_i C_i Y_i(\alpha, \varphi) \tan \theta_{hkl}$$

(4)

where $Y_i(\alpha,\varphi)$ are the symmetrized spherical harmonics and $C_i$ are the refined parameters.

The pure strain-induced profile for a certain $hkl$ reflection was obtained by convoluting the symmetrical Gaussian function and the exponential function defined at the corresponding $\theta_{hkl}$. This convoluted profile corresponds to the variation of the lattice parameters. The population density function ($pdf$) on the 2$\theta$ scale for an $hkl$ interplanar spacing of one phase is given by

$$pdf(2\theta)_{hkl} = \frac{1}{E \sqrt{2\pi}} e^{-(2\theta - 2\theta_m)^2/2E^2} \Theta(f(\theta))$$

(5)

where $E$ is the refined symmetrical strain parameter defined in eq 2 and $f(\theta)$ is given by eq 3. The population densities of the $a$, $b$, and $c$ lattice parameters for one phase are given by $pdf_{a00}$, $pdf_{b00}$, and $pdf_{c00}$, respectively. The total population density (considering both Li-rich and Li-poor phases) is given by

$$pdf(2\theta) = SF_1 \times pdf(2\theta)_{hkl1} + SF_2 \times pdf(2\theta)_{hkl2}$$

(6)

where $SF_1$ and $SF_2$ are the scale factors for the Li-rich and Li-poor phases, respectively. Bragg's law was used to convert the scale from 2$\theta$ to $d$-spacing.

The whole-power-pattern fitting of the in situ diffraction patterns within the 2$\theta$ range between 35' and 15' was carried out sequentially using the TOPAS structural refinement package.

2.5. Simulations of XRD Peak Profiles for a Coherent Interface. A cubic particle with edges parallel to the $a$, $b$, and $c$ axes of the olivine crystal structure was used for the simulation. Each edge was 100 nm long. The interface was assumed to be perpendicular to the [001] direction. The delithiation process was assumed to vary linearly with the width of the interface, $x_0$, and the changes in the unit cell volumes as a function of capacity are noticeable larger than expected as a result of side reactions. Therefore, the particles must have a continual and gradual shift of the unit cell volume is observed during the first few cycles.

For a 0$\theta$ reflection, the diffraction power as a function of diffraction angle 2$\theta$ can be expressed as

$$P(2\theta) = \frac{K}{\sin^2 \theta} \sum_m \sum_{m'} \int_{-\infty}^{\infty} f_m f_{m'} e^{i(2\pi/\lambda)(2 \sin \theta)(R_m - R_{m'})}$$

(8)

where the subscripts $m$ and $m'$ represent the indices of the unit cells, $f_m$ is the structure factor of unit cell $m$, $R_m$ is the position coordinate of unit cell $m$, $\lambda$ is the X-ray wavelength, and $K$ is a factor independent of $\theta$. The summation is performed over all of the unit cells in the particle. The structure factor $f$ for the 020 reflection was assumed to vary linearly with the Li composition $c$:

$$P(c) = (1 - c)f(0) + cf(1)$$

(9)

where $f(0)$ is the structure factor for the 020 reflection of Fe$_0$Co$_{50}$PO$_4$ and $f(1)$ is that for LiFe$_{0.95}$Co$_{0.05}$PO$_4$.

3. RESULTS AND DISCUSSION

3.1. Synthesis and Characterization of LiFe$_{x}$Co$_{(1-x)}$PO$_4$. The carbon-coated LiFe$_{0.05}$Co$_{0.95}$PO$_4$ ($x = 0, 0.05, 0.125, 0.25, 0.5, 0.75, 0.875, 0.95$) materials were synthesized via solid-state synthesis. Additional heating steps were required for higher Co compositions to decrease the extent of impurities present in the product (including Li$_3$PO$_4$ as shown in Figure S4). The average particle size of LiFePO$_4$ is approximately 120 nm, as determined from scanning electron microscopy (SEM) images of a LiFePO$_4$ electrode taken at different magnifications (shown in the SI). The large distribution of particle sizes (from ~50 to 350 nm) and spherical-type morphology are expected for the solid-state synthesis. SEM images of the as-synthesized carbon-coated LiCoPO$_4$ powder indicate that the particle size is smaller than 50 nm (see Figure S5). Therefore, the particle sizes of all of the LiFe$_{x}$Co$_{(1-x)}$PO$_4$ compositions are assumed to be in the nanoparticulate regime.

3.2. Fe-Rich LiFe$_{x}$Co$_{(1-x)}$PO$_4$ ($x = 1, 0.95, 0.875$). 3.2.1. First Charge. In situ XRD patterns of the Fe-rich substituted olivines (LiFePO$_4$, LiFe$_{0.95}$Co$_{0.05}$PO$_4$, and LiFe$_{0.875}$Co$_{0.125}$PO$_4$) cycled at a rate of C/20 for the first cycle and up to 100 mA h$^{-1}$ g$^{-1}$ of the second charge are presented in Figure 2a–c. The 2$\theta$ range in Figure 2a shows the 020 and 211 reflections of the lithiated and delithiated phases. Only the FePO$_4$ and LiFePO$_4$ reflections are observed when LiFePO$_4$ is charged at this low rate (Figure 2a). This is characteristic of a “two-phase reaction” at the electrode level, the delithiated phase being formed at the expense of the fully lithiated phase with no significant peak shift and broadening (as discussed in the Introduction). We cannot determine the exact mechanism of the reaction at the single-particle level, i.e., we cannot distinguish whether two phases exist within the same particles or in different particles, at intermediate states of charge, as depicted in schemes A and B in Figure 1, because of the limited resolution of the experimental setup and the limited fraction of the sample that is expected to be undergoing a transformation (delithiation) at one time at the low rates used here. In both LiFe$_{0.95}$Co$_{0.05}$PO$_4$ and LiFe$_{0.875}$Co$_{0.125}$PO$_4$, the evolution of the intensities and positions of the reflections of the end-member lithiated phase on charging is similar to that observed for LiFePO$_4$. In contrast, the peak positions of the delithiated phases deviate noticeably from the positions of Fe$_{0.05}$Co$_{0.95}$PO$_4$, shifting toward that of the Li$_0$ phase as charging proceeds. The extent of the deviations becomes more significant as the Co content increases.

Rietveld refinements were carried out using the XRD data, and the changes in the unit cell volumes as a function of capacity are plotted in Figure 2d–f. The theoretical capacity of LiFe$_{x}$Co$_{(1-x)}$PO$_4$ is between 167 and 170 mA h$^{-1}$ g$^{-1}$, however, as shown in Figure 2ef, the charge capacities for the Co-containing materials are noticeably larger than expected as a result of side reactions (potentially including oxidation of the electrolyte above 4.6 V, the formation of a solid electrolyte interphase (SEI) at the cathode,$^{6,7}$ metal dissolution,$^{38}$ and oxidation of carbon). Nevertheless, the discharge capacities are among the highest recorded for these materials (~160 mA h$^{-1}$ g$^{-1}$; Table S1 and Figure S6), suggesting that the reversibility of the electrochemical reactions is not significantly affected by the side reactions, at least in the first few cycles.

Since the Fe$^{2+} \rightarrow$ Fe$^{3+}$ and Co$^{2+} \rightarrow$ Co$^{3+}$ redox reactions occur at ~3.5 and ~4.8 V, respectively, in the olivine structure, Fe$^{2+}$ is oxidized first upon charging. Therefore, the particles must have a Li content of Li$_{1-x}$Fe$_x$Co$_{(1-x)}$PO$_4$ at the end of the 3.6 V process because xLi per formula unit is deintercalated during the Fe plateau. A continual and gradual shift of the unit cell volume is observed going from the Li$_{1-x}$(Fe$^{2+}$)$_x$(Co$^{3+}$)$_{(1-x)}$PO$_4$ phase to the fully delithiated (Fe$^{2+}$)$_x$(Co$^{3+}$)$_{0.5(1-x)}$PO$_4$ material upon charging at >3.5 V.
Figure 2. In situ XRD data for the first cycle and up to 100 mA h$^{-1}$ g$^{-1}$ of the second charge of the Fe-rich LiFe$_{0.875}$Co$_{0.125}$PO$_4$ phases ($x = 1, 0.95$, and $0.875$ in (a–c), respectively) while cycling at a rate corresponding to C/20. Here and in all of the XRD patterns presented in this paper, the $x$ axis displays the 2$\theta$ region = 7.8–8.3° ($d = 0.413609$ Å), showing the characteristic 202 and 211 reflections of the end-member phases. The $y$ axis represents the scan number. These scan numbers correspond to the red crosses (and blue boxes) marked on the electrochemical data in (d–f). The black dotted vertical lines indicate the positions of the peaks of the fully lithiated and delithiated phases. Unit cell volume changes as a function of capacity (in mA h$^{-1}$ g$^{-1}$) for $x = 1, 0.95$, and $0.875$ are shown in (d–f), respectively. The black line represents the electrochemistry, while the red crosses, blue squares represent the volumes of the Li$_{1-x}$Fe$_x$PO$_4$, Fe$_{1-x}$Co$_x$PO$_4$, and Co$_x$PO$_4$ phases, respectively. Variations of the $b$ lattice parameter, plotted as the population density, as a function of the scan number for $x = 1, 0.95$, and $0.875$ are shown in (g–i) respectively (extracted from refinements using whole-powder-pattern fits). The $b$ lattice parameters for the lithiated and delithiated phases are $\sim 6.0$ and $5.8$ Å, respectively. The (a–c) black dashed horizontal lines indicate the end of the charge, while the red dashed lines represent the end of the discharge. The red, green, and blue bars alongside the figure show when the Li$_{1-x}$, Li$_{1-\delta}$, and Li$_{1-\delta}$Fe$_{1-\delta}$Co$_{1-\delta}$PO$_4$ phases, respectively, are being consumed.

(Figures 2e,f), which is indicative of a single-phase transition between the two Li stoichiometries at the bulk (electrode) level (mechanism C) for the Co$^{3+}$/Co$^{4+}$ process. Ex situ $^{31}$P NMR spectra of the fully charged material confirm the complete transformation of these phases to Fe$_{0.125}$Co$_{0.875}$PO$_4$ (Figure S7).

3.2.2. Subsequent Cycles: The Discrete Nonequilibrium Single-Phase Mechanism (D). As shown in Figure 2a–c the first discharge and second charge appear to have different in situ XRD responses compared with the first charge. The sharp reflections from the pristine structure are not reformed after the first cycle, instead, the reflections are broader and asymmetric (the individual diffraction patterns are plotted in Figure S8). Additionally, low-intensity, continually shifting peaks are observed between the Li$_{1-x}$Fe$_x$PO$_4$, Li$_{1-x}$Fe$_x$Co$_{1-x}$PO$_4$, and Fe$_x$Co$_{1-x}$PO$_4$ reflections in the first discharge and second charge, which correspond to compositions with intermediate stoichiometries. The patterns qualitatively resemble those observed by Liu et al. during very fast cycling of LiFePO$_4$ this phenomenon being attributed to the nonequilibrium single-phase, particle-by-particle delithiation mechanism of LiFePO$_4$ (mechanism D).

Following the work of Liu et al., we used whole-powder-pattern fitting to obtain population densities describing the fractions of the sample exhibiting different cell parameters. The population densities of the $b$ lattice parameters for LiFePO$_4$, Li$_{0.95}$Fe$_{0.05}$PO$_4$, and Li$_{0.875}$Fe$_{0.125}$PO$_4$ plotted as a function of scan number for the first 1.5 cycles are shown in Figure 2g–i, respectively. Liu et al. observed that Li$_{1-x}$FePO$_4$ can accommodate a larger deviation in the $a$, $b$, and $c$ lattice parameters from the end member LiFePO$_4$ than Li$_{1-x}$Fe$_x$PO$_4$ from FePO$_4$ (after the first charge). This is supported by phase-field simulations and in situ XRD experiments, both of which show that Li$_{1-x}$FePO$_4$ is able to exist in a larger single-phase region than Li$_{1-x}$FePO$_4$. When 5% Co is substituted onto the Fe site, the Li$_{0.05}$Fe$_{0.95}$Co$_{0.05}$PO$_4$ intermediate can tolerate an even larger range of cell parameters beyond those observed for LiFe$_{0.95}$Co$_{0.05}$PO$_4$ and Fe$_{0.95}$Co$_{0.05}$PO$_4$. This becomes apparent upon discharge. The effect is more pronounced for Li$_{0.875}$Fe$_{0.125}$PO$_4$ which upon discharge first shows bulk single-phase (solid solution) behavior (mechanism C) between fully delithiated Fe$_{0.875}$Co$_{0.125}$PO$_4$ and the intermediate Li$_{0.125}$Fe$_{0.875}$Co$_{0.125}$PO$_4$ (i.e., a continuous shift of the diffraction peaks, with a narrow distribution in the $b$ lattice parameter); this is then followed by an asymmetric broadening in the diffraction peaks, reflecting a large dispersion of lattice parameters/d-spacings. This asymmetric broadening is a deviation from the conventional two-phase reaction and is suggestive of a single-phase, nonequilibrium transformation between Li$_{0.125}$Fe$_{0.875}$Co$_{0.125}$PO$_4$ and Fe$_{0.875}$Co$_{0.125}$PO$_4$ (mechanism D).

The results in Figure 2 strongly suggest that the nonequilibrium single-phase behavior (D), previously observed only at high rates, is present even under the application of a low current. The presence of Co substituted into the LiFePO$_4$ structure results in more particles reacting at the same time, making it easier to detect the single-phase behavior. However, there is still evidence of the nonequilibrium single-phase transition at low cycle rates even for LiFePO$_4$. Interestingly, more particles react simultaneously in the first discharge and second charge compared with the first charge. This same phenomenon was also observed at high rates for LiFePO$_4$, i.e., the asymmetric peak broadening (and hence the nonequilibrium limits of the solid solution) is more significant in the first discharge and subsequent cycles than in the first charge. The origin of this phenomenon is not clear, but it may be related to the presence of nonequilibrium Li$^+$ ion concentrations within the electrolyte, particularly when the experiments are performed at high rates; simulations are required to explore this hypothesis. The introduction of disorder in the lattice via the formation of defects (particularly in the case of the Co-substituted materials) or due to the presence of residual Li ions or vacancies in the delithiated and lithiated materials, respectively, may also result in an increase in the entropy of the system and a reduction in the tendency of the system to order, promoting solid-solution behavior.
Interestingly, both intermediates are formed during the Fe^{2+}/Fe^{3+} redox plateau, with the theoretical capacity of 167.75 mA h. Ninety-one percent of the theoretical capacity (i.e., 153 mA h) is detected in Figure 3bd during the first charge. Despite a capacity of over 91% of the theoretical capacity, the electrochemistry and in situ XRD patterns for the first charge of the highly substituted olivine material, LiFe_{0.25}Co_{0.75}PO_4, are shown in Figure 3a,b. In agreement with the Fe-rich materials, the intermediate, Li_{0.75}Fe_{0.25}Co_{0.75}PO_4, is seen at the end of the Fe^{2+}/Fe^{3+} redox plateau. Interestingly, a second intermediate is also observed, which on the basis of our previous study of LiCoPO_4, is Li_{2/3}CoPO_4 intermediate. This is in very good agreement with the stoichiometry Li_{2/3}Fe_{0.5}Co_{0.5}PO_4, obtained using Vegard’s law and the cell parameters of FePO_4 and CoPO_4. The red, green, and purple bars alongside the figure show when the Li_{1+/−}, Li_{1−/−}, and Li_{2/3}Fe_{0.5}Co_{0.5}PO_4 phases, respectively, are being consumed in the reaction.

### 3.3. Highly Co-Substituted Phases

#### 3.3.1. LiFe_{0.25}Co_{0.75}PO_4 and LiFe_{0.5}Co_{0.5}PO_4

The electrochemistry and in situ XRD patterns for the first charge of the highly substituted olivine material, LiFe_{0.25}Co_{0.75}PO_4, are shown in Figure 3a,b. In agreement with the Fe-rich materials, the intermediate, Li_{1−/−}Fe_{0.75}Co_{0.25}PO_4, is seen at the end of the Fe^{2+}/Fe^{3+} redox plateau. Interestingly, a second intermediate is also observed, which on the basis of our previous study of LiCoPO_4, in which a Li_{2/3}CoPO_4 intermediate was identified, has the Li stoichiometry Li_{2/3}Fe_{0.5}Co_{0.5}PO_4. Using Vegard’s law and assuming a constant variation in the lattice parameters across the series Fe_{x}Co_{1−x}PO_4 (0 ≤ x ≤ 1) and LiFe_{0.25}Co_{0.75}PO_4 (0 ≤ y ≤ 1), we can estimate the expected lattice parameters for Fe_{0.25}Co_{0.75}PO_4 (the resulting approximate position of the 020 reflection is shown with a white ellipse in Figure 3).

Surprisingly, the reflections from Fe_{0.25}Co_{0.75}PO_4 are difficult to detect in Figure 3d during the first charge, despite a capacity of over 91% of the theoretical capacity (i.e., 153 mA h g^{-1}), compared with the theoretical capacity of 167.75 mA h g^{-1} in both the first and second cycles. The fully delithiated phase is, however, more clearly seen in the second cycle (see Figure S9), and close inspection of the individual XRD patterns at the end of first charge, as shown in Figure S9, does reveal small, weak reflections at the same positions observed for Fe_{0.25}Co_{0.75}PO_4 in the second cycle.

The in situ XRD patterns for the first charge of LiFe_{0.25}Co_{0.75}PO_4 (Figure 3d) also contain reflections from two intermediate compositions in addition to those of the fully delithiated and delithiated materials. The basis of Vegard analysis, they are assigned to Li stoichiometries of Li_{1/2} and Li_{1−/−}. This is in very good agreement with the first charge of the LiFe_{0.25}Co_{0.75}PO_4 material. Interestingly, both intermediates are formed during the Fe^{2+}/Fe^{3+} redox plateau, with Li_{1/2}Fe_{0.5}Co_{0.5}PO_4 forming first, followed by Li_{0.48}Fe_{0.25}Co_{0.75}PO_4. The Li_{0.48}Fe_{0.25}Co_{0.75}PO_4 phase forms at a charge capacity of 137 mA h g^{-1} (which is 81.3% of the theoretical capacity of 168.5 mA h g^{-1}). However, as already discussed, the capacities of the first charge are significantly higher than the theoretical capacities as a result of side reactions, SEI formation, and/or electrolyte decomposition. Therefore, in order to determine the Li composition of this intermediate, we use (a) the unit cell volume, which by Vegard’s law indicates that the phase has a stoichiometry of Li_{1−/−}, and (b) the voltage at which the Li_{0.5}Fe_{0.5}Co_{0.5}PO_4 phase forms, ~4.78 V (i.e., after the Fe^{2+}/Fe^{3+} redox plateau and before the higher-voltage Co^{2+}/Co^{3+} plateau).

#### 3.3.2. The Coherent Interface

A whole-powder-pattern fit was performed for LiFe_{0.25}Co_{0.75}PO_4 and the population density plot of the b lattice parameter is shown as a function of scan number in Figure 4a. The first intermediate, Li_{0.75}Fe_{0.25}Co_{0.75}PO_4, is formed via a two-phase reaction from the fully lithiated phase. It can be seen that LiFe_{0.25}Co_{0.75}PO_4 and Li_{0.75}Fe_{0.25}Co_{0.75}PO_4 have significant Li solubility ranges. To study this first phase transition more closely, the individual XRD patterns (in the 2θ range containing the 020 and 211 reflections) for the beginning of charge (LiFe_{0.25}Co_{0.75}PO_4 → Li_{0.75}Fe_{0.25}Co_{0.75}PO_4) are shown in Figure 4b. When the Li_{0.75}Fe_{0.25}Co_{0.75}PO_4 phase first nucleates in the parent phase (fully lithiated LiFe_{0.25}Co_{0.75}PO_4 particles), the volume extends toward the volume of LiFe_{0.25}Co_{0.75}PO_4, which results in a shift in the XRD peak position (Figure 4b), suggesting the presence of a coherent interface between the two phases within the same particle (mechanism E in Figure 1 and Figure 4b).

The same is observed when LiFe_{0.25}Co_{0.75}PO_4 is the minority phase in the Li_{0.75}Fe_{0.25}Co_{0.75}PO_4 particle. The distortion in the crystal structure of the minority phase as it nucleates in the majority phase arises from the structural elasticity in the minority phase, which allows it to be accommodated in the majority phase of the particle while reducing the energy at the interface of the two phases. Hence, there is both a change in intensity in the Bragg diffraction peaks (as the nucleating phase grows at the expense of the parent phase) and a shift in the peak...
positions due to the structural distortions. This phenomenon is observed to a degree in all of the two-phase reactions but is much more pronounced in phase transformations of the highly substituted samples; it was nonetheless clearly visible in the LiCoPO₄ to Li₁/₃CoPO₄ reaction.²⁴

XRD peak profile simulations were carried out on 100 nm cubic LiFe₀.₂₅Co₀.₇₅PO₄ particles. Two-phase reactions between LiFe₀.₂₅Co₀.₇₅PO₄ and Li₀.₇₅Fe₀.₂₅Co₀.₇₅PO₄, between Li₀.₇₅Fe₀.₂₅Co₀.₇₅PO₄ and Li₂/₃Fe₀.₂₅Co₀.₇₅PO₄, and between Li₀.₇₅Fe₀.₂₅Co₀.₇₅PO₄ and Fe₀.₂₅Co₀.₇₅PO₄ were modeled with a coherent interface ranging between 5 and 200 nm in length as described in section 2.5. The length of the interface is the quantity L that appears in eq 7, which describes a concentration profile along the a axis of the particle. When the length of the interface approaches or becomes greater than the size of the coherent interface, the peaks continually and gradually shift from the reactants to the products, i.e., the response approaches that expected for a single-phase solid solution. (Representative concentration profiles are illustrated in Figure S10.)

It should be noted that when the coherent interface is 200 nm in size, the peaks continually and gradually shift from the reactants to the products, i.e., the response approaches that expected for a bulk single-phase mechanism (scheme C). The results for the evolution of the 020 XRD peak are shown in Figure 5. There is reasonable agreement between the simulation and the experimental data of the coherent interface: the peaks of the minority phase distort significantly toward the values of the majority phase (Figure 5c). The simulations suggest that the LiFe₀.₂₅Co₀.₇₅PO₄ → Li₁₋ₓFeₓCo₁₋ₓPO₄ reaction proceeds via the two-phase mechanism with a coherent interface for which 60 < L < 100 nm. In contrast, the Li₁₋ₓFeₓCo₁₋ₓPO₄ → Li₀.₇₅FeₓCo₀.₇₅PO₄ and Li₀.₇₅FeₓCo₀.₇₅PO₄ → FeₓCo₁₋ₓPO₄ reactions both show continuous and gradual shifts in the XRD peaks, corresponding to the two-phase mechanism with a coherent interface for which L = 200 nm, i.e., the bulk solid-solution mechanism.

It should be noted that we have assumed the nucleating phase growing within the majority component has the same composition and thus cell parameters as the bulk phase, with the composition varying across the interface. It is also important to emphasize that more than one coherent interface may exist in one particle simultaneously.

3.3.3. Systematic Analysis of Cell Parameter Changes. The same analysis as described in section 3.3.1 for LiFe₀.₂₅Co₀.₇₅PO₄ and LiFe₀.₅Co₀.₅PO₄ was carried out for all of the other LiFeₓCo₁₋ₓPO₄ phases (x = 1, 0.95, 0.875, 0.75, 0.125, 0.05, 0). The cell parameters for the intermediates and end-member phases for all nine ratios were extracted from Rietveld refinements of the XRD patterns (all of the raw data is shown in Figure S11). The unit cell volumes of the end members and intermediates extracted from the Rietveld refinements of the XRD patterns are plotted against Fe content (x) in Figure 6. The phases corresponding to LiFe₀.₅Co₀.₅PO₄, Li₀.₇₅Fe₀.₂₅Co₀.₇₅PO₄, Li₀.₇₅Fe₀.₅Co₀.₅PO₄, and Fe₀.₂₅Co₀.₇₅PO₄ were shown by red, green, purple, and blue data points, respectively. There is a linear increase in the volume of LiFeₓCo₁₋ₓPO₄ (shown in red) with increasing x. This is in agreement with the literature⁴¹,⁴² and is a result of the homogeneous mixing of the transition metals in the olivine structure (assuming that Vegard’s law applies). Similarly, the a and b lattice parameters (shown in Figure S12) increase with increasing Fe content because of the larger ionic radius of Fe²⁺ compared with Co²⁺ (92 and 88.5 pm, respectively, assuming a high-spin ion in an octahedral environment).³⁸ Interestingly, the c axis decreases with increasing Fe content, and although the origin for this behavior is unknown, it is thought to be related to the stiffness of the P–O bonds (effectively rigid PO₄ tetrahedra) and the shared edges between the PO₄ and MO₆ polyhedra,⁴¹ with the phosphate ions acting to separate or pillar the chains of edge-sharing MO₆ octahedra. The changes in the volume for Fe₀.₂₅Co₁₋ₓPO₄ (blue dashed line) display the same linear gradient as those for the lithiated phases, presumably because the difference in Co and Fe cation sizes is identical for the divalent and trivalent cations. The volume of the Li₂/₃FeCo₁₋ₓPO₄ intermediate (observed for the Co-majority materials, 0 ≤ x ≤ 0.5) lies two-thirds of the way between those of the fully lithiated and delithiated phases
and the volume of the Li\textsubscript{1-x}Fe\textsubscript{x}Co\textsubscript{1-x}PO\textsubscript{4} intermediates varies linearly between those of LiCoPO\textsubscript{4} and FePO\textsubscript{4} with increasing Fe content (green dashed line). This simple analysis using Vegard’s rule is in good agreement with the Li stoichiometries assigned to the intermediates observed during the first charge of LiFe\textsubscript{x}Co\textsubscript{1-x}PO\textsubscript{4} (\(x = 0.95, 0.875, 0.75, 0.5, 0.125, 0.05\)).

Although no obvious trends for the compositions and cell parameters of the different intermediates emerge when each composition is studied individually, the systematic examination of the phases as a function of Fe:Co ratio reveals clear correlations with respect to the Li composition and cell parameters of the intermediate phases. The percentage differences in the \(a\), \(b\), and \(c\) axes, the \(ab\), \(ac\), and \(bc\) planes, and the volumes of the two intermediates and the end-member structures relative to LiFePO\textsubscript{4} have been calculated and are shown in Figure S13. As was observed in the LiFe\textsubscript{Mn\textsubscript{1-x}}PO\textsubscript{4} materials\textsuperscript{14} and for LiCoPO\textsubscript{4}\textsuperscript{24} there is a very small difference (<2%) in the \(bc\) plane among all of the structures. This strongly suggests that when there is a coherent interface, it is likely to be in this plane, resulting in the lowest size mismatch and therefore the lowest strain compared with interfaces along the \(ab\) and \(bc\) planes. This arises from the contraction of the \(c\) axis with both increasing Co content and decreasing Li content from LiFePO\textsubscript{4} and the smaller expansion along the \(b\) axis compared with the \(a\) axis. We now consider separately how the delithiation mechanisms vary among the starting, intermediate, and end-member phases, comparing the mechanisms as a function of Co content.
3.4. LiFe$_{0.05}$Co$_{0.95}$PO$_4$ Delithiation Mechanisms upon Charging. 3.4.1. Delithiation Mechanisms between the Two Intermediates Li$_{1-x}$Fe$_x$Co$_1$PO$_4$ and Li$_{2/3}$Fe$_x$Co$_1$PO$_4$. As shown in Figure 6, when the four substituted olivines LiFe$_{0.01}$Co$_{0.98}$PO$_4$, LiFe$_{0.125}$Co$_{0.875}$PO$_4$, LiFe$_{0.25}$Co$_{0.75}$PO$_4$, and LiFe$_{0.375}$Co$_{0.625}$PO$_4$ are delithiated, two intermediates are observed, Li$_{1-x}$Fe$_x$Co$_{1-x}$PO$_4$ and Li$_{2/3}$Fe$_x$Co$_{1-x}$PO$_4$. These were extracted from refinements using whole-powder-pattern fits. The plot at the bottom shows the volume changes between the intermediate phases. The gray-shaded area indicates the phases being investigated in this section and whose cell parameters are shown in this figure. The green and purple bars alongside the plots indicate when the Li$_{1-x}$ and Li$_{2/3}$Fe$_x$Co$_{1-x}$PO$_4$ phases, respectively, are being consumed in the reaction.

Figure 7. Variations in the b lattice parameter, plotted as population density, as a function of the scan number for LiFe$_{0.05}$Co$_{0.95}$PO$_4$, LiFe$_{0.125}$Co$_{0.875}$PO$_4$, LiFe$_{0.25}$Co$_{0.75}$PO$_4$, and LiFe$_{0.375}$Co$_{0.625}$PO$_4$. These were extracted from refinements using whole-powder-pattern fits. The plot at the bottom shows the volume changes between the intermediate phases. The gray-shaded area indicates the phases being investigated in this section and whose cell parameters are shown in this figure. The green and purple bars alongside the plots indicate when the Li$_{1-x}$ and Li$_{2/3}$Fe$_x$Co$_{1-x}$PO$_4$ phases, respectively, are being consumed in the reaction.
LiFe$_{0.75}$Co$_{0.25}$PO$_4$ to LiFe$_{0.5}$Co$_{0.5}$PO$_4$. A continuous shift in the purple bars alongside the plots show when the Li$_1$ because of time limitations at the synchrotron, and for LiCoPO$_4$.

For both LiFe$_{0.75}$Co$_{0.25}$PO$_4$ and LiFe$_{0.5}$Co$_{0.5}$PO$_4$, single-phase lattice parameters can be seen in going from Li$_1$ to Li$_b$. As discussed in section 3.4.1, the single-phase mechanism is preferred because of (i) the disorder of Li$^+$/vacancies and Fe$^{3+}$/Co$^{3+}$ in Li$_{1-x}$Fe$_x$Co$_{1-x}$PO$_4$ which helps favor the single-phase mechanism during the oxidation of Co$^{3+}$, and (ii) the small change in volume. For both LiFe$_{0.875}$Co$_{0.125}$PO$_4$ and LiFe$_{0.125}$Co$_{0.875}$PO$_4$, single-phase behavior is also observed upon delithiation of Li$_{1-x}$Fe$_x$Co$_{1-x}$PO$_4$ but fewer particles appear to react at once compared with LiFe$_{0.5}$Co$_{0.5}$PO$_4$ (i.e., the number of reacting particles decreases with decreasing Fe content in going from LiFe$_{0.875}$Co$_{0.125}$PO$_4$ to LiFe$_{0.125}$Co$_{0.875}$PO$_4$). A continuous shift in the lattice parameters can be seen in going from Li$_{1-x}$Fe$_x$Co$_{1-x}$PO$_4$ to Fe$_0.75$Co$_{0.25}$PO$_4$ whereas for the Li$_{0.5}$Fe$_0.5$Co$_{0.5}$PO$_4$ → Fe$_0.5$Co$_{0.5}$PO$_4$ reaction significant asymmetric deviations of the end-member phases toward each other are observed. This implies that the single-phase mechanism is to a degree occurring discretely between particles (scheme D) rather than simultaneously (i.e., at the bulk level, scheme C). This change from particles reacting discretely compared with simultaneously is even more pronounced during the reaction of Li$_{1-x}$Fe$_x$Co$_{1-x}$PO$_4$ to form Fe$_0.125$Co$_{0.875}$PO$_4$.

To summarize, during the oxidation of Co$^{2+}$ to Co$^{3+}$, a single-phase (solid-solution) mechanism occurs within individual particles to form fully delithiated Fe$_{1-x}$Co$_x$PO$_4$. At low levels of Fe substitution (i.e., LiFe$_{0.125}$Co$_{0.875}$PO$_4$), the reaction occurs discretely, particle-by-particle. As the level of Fe substitution increases, more particles react simultaneously, resulting in increasingly more bulk single-phase-like behavior. At high Fe contents, i.e., LiFe$_{0.875}$Co$_{0.125}$PO$_4$, essentially ideal single-phase behavior is observed.

### 3.4.3. Delithiation Mechanisms Occurring during the Reaction of Fully Lithiated LiFe$_{1-x}$Co$_x$PO$_4$

Finally, we examine the first delithiation reaction that occurs upon charging of LiFe$_{1-x}$Co$_x$PO$_4$ for $x = 1, 0.95, 0.875, 0.75, 0.5, 0.25, 0.125$, and 0.05. A whole-powder-pattern fit was performed for all eight of the materials, and the population density plots of the $b$ lattice parameter as a function of the scan number are shown in Figure 9 for the initial delithiation of the pristine LiFe$_{1-x}$Co$_x$PO$_4$ phase. LiCoPO$_4$ is not included since we focus here on the mechanism that occurs on the Fe$^{2+}$/Fe$^{3+}$ oxidation plateau.

As discussed in section 3.2.2, the delithiation of the Fe-rich materials (LiFePO$_4$, LiFe$_{0.125}$Co$_{0.875}$PO$_4$ and LiFe$_{0.875}$Co$_{0.125}$PO$_4$) appears to occur via a simple “two-phase” reaction (as only the two end-member phases are observed, as depicted in mechanism B). However, further analysis of the first discharge and second charge reveals that the transformation between the two phases (between LiFePO$_4$ and FePO$_4$ and between LiFe$_{1-x}$Co$_x$PO$_4$ and Li$_{1-x}$Fe$_x$Co$_{1-x}$PO$_4$ for $x = 0.95$ and 0.875) occurs via the non-equilibrium single-phase mechanism (D). Since very few particles react at once, the two end-member phases dominate the reaction. As the Co-substitution level increases (from 0 to 0.05 to 0.125), more particles react at once and the asymmetric deviations from
the end-member phases toward each other are more discernible, even in the first charge (Figure 9 for LiFe$_{0.875}$Co$_{0.125}$PO$_4$).

The delithiation mechanisms for LiFe$_{0.75}$Co$_{0.25}$PO$_4$ and LiFe$_{0.5}$Co$_{0.5}$PO$_4$ at the onset of charge involve a bulk shift of the lattice parameters from those of the end members, LiFe$_{x}$Co$_{1-x}$PO$_4$ and Li$_{1-x}$Fe$_{x}$Co$_{1-x}$PO$_4$, as well as an asymmetric broadening in the parameters toward each other. In section 3.3, we ascribed the behavior seen for the delithiation of LiFe$_{0.25}$Co$_{0.75}$PO$_4$ to form Li$_{0.75}$Fe$_{0.25}$Co$_{0.75}$PO$_4$ to that of a two-phase reaction occurring in the presence of a coherent interface. Therefore, the behavior of LiFe$_{0.75}$Co$_{0.25}$PO$_4$ and LiFe$_{0.5}$Co$_{0.5}$PO$_4$ is likely to be intermediate between those of the Fe-rich materials and LiFe$_{0.25}$Co$_{0.75}$PO$_4$. We will discuss in more detail how these mechanisms are related in section 3.5.

LiFe$_{0.05}$Co$_{0.95}$PO$_4$ reacts via a bulk single-phase mechanism (mechanism C) to form Li$_{0.95}$Fe$_{0.05}$Co$_{0.95}$PO$_4$ intermediate, as shown by a continuous shift in the lattice parameters, whereas LiFe$_{0.125}$Co$_{0.875}$PO$_4$ has more “two-phase”-like behavior, as shown by the coexistence of the LiFe$_{0.125}$Co$_{0.875}$PO$_4$ and Li$_{0.875}$Fe$_{0.125}$Co$_{0.875}$PO$_4$ lattice parameters, with some shift in the parameters toward each other. As the Fe content decreases, two phenomena occur: the difference between the cell parameters of LiFe$_{x}$Co$_{1-x}$PO$_4$ and Li$_{1-x}$Fe$_{x}$Co$_{1-x}$PO$_4$ decreases and the substitution levels (i.e., the disruption in the lattice) decrease. The former favors the single-phase mechanism (as observed for LiFe$_{0.05}$Co$_{0.95}$PO$_4$) and the latter results in a shorter coherent interface (as the lattice has fewer dopant Fe particles, leading to reduced structural elasticity) in the two-phase reaction, as seen for LiFe$_{0.125}$Co$_{0.875}$PO$_4$. These two competing phenomena must cause the apparent “break” in trend for LiFe$_{0.125}$Co$_{0.875}$PO$_4$.

3.5. Discussion of How the Mechanisms Are Related and Interconvert. As demonstrated in section 3.4, there is not a sharp cutoff between the various mechanisms as the Co content increases. In Figure 10 we summarize how the mechanisms are interconnected. From previous studies$^{3,6}$ of partially charged samples of LiFePO$_4$, we know that as we increase the particle size, the two end-member phases (i.e., FePO$_4$ and LiFePO$_4$) are able to coexist within a particle rather than existing in separate particles (the transition from scheme B to scheme A in Figure 10).

We saw in section 3.2 that at low cycle rates, nanoparticulate LiFePO$_4$ delithiates via the single-phase mechanism with few particles reacting at once (scheme B). As the Co content increases in going from LiFePO$_4$ to LiFe$_{0.95}$Co$_{0.05}$PO$_4$ and LiFe$_{0.875}$Co$_{0.125}$PO$_4$ more particles react simultaneously during delithiation of the fully lithiated phase on the plateau of the Fe$^{2+}$/Fe$^{3+}$ oxidation reaction, as demonstrated by the pathway from scheme B to scheme D in Figure 10. The studies by Liu et al.$^{12}$ showed that as the current applied to the system increases, a more pronounced effect (i.e., even more particles react simultaneously) is seen when forming the fully delithiated phase during the Co$^{2+}$/Co$^{3+}$ oxidation reaction for increasing Fe content, for $x =$ 0.125, 0.5, 0.75, and 0.875 (scheme D to scheme C), eventually leading to the bulk single-phase mechanism (C) for the transformation between Li$_{0.125}$Fe$_{0.875}$Co$_{0.125}$PO$_4$ and Fe$_{0.875}$Co$_{0.125}$PO$_4$. 

![Figure 9. Variations in the b lattice parameter, plotted as population density, as a function of the scan number for LiFe$_{x}$Co$_{1-x}$PO$_4$ with $x =$ 1, 0.95, 0.875, 0.75, 0.5, 0.25, 0.125, and 0.05. These were extracted from refinements using whole-powder-pattern fits. The plot at the top right shows the volume changes, and the gray-shaded area highlights those that occur when the fully lithiated phase is delithiated. The red bars alongside the plots indicate that it is the Li$_{x}$Fe$_{1-x}$PO$_4$ phase that is being consumed as the material is delithiated.]
Using Figure 10, we are now able to better understand the trend in the mechanisms observed in Figure 9. We know that increasing the Co content in the substituted olivines increases the number of particles that react simultaneously during the plateau of the Fe$^{2+}$/Fe$^{3+}$ oxidation reaction (scheme $B \rightarrow scheme D$), and we know that a two-phase mechanism containing a coherent interface is observed when LiFe$_{0.25}$Co$_{0.75}$PO$_4$ is delithiated to form Li$_{0.75}$Fe$_{0.25}$Co$_{0.75}$PO$_4$ (scheme $E$). Therefore, between LiFe$_{0.75}$Co$_{0.25}$PO$_4$ and LiFe$_{0.5}$Co$_{0.5}$PO$_4$, the mechanism is transitioning from $D$ to $E$: both more particles are reacting at once and the intermediate lithium compositions are now able to coexist within a particle rather than between particles. As we further increase the Co content in going from LiFe$_{0.25}$Co$_{0.75}$PO$_4$ to LiFe$_{0.05}$Co$_{0.95}$PO$_4$, we move from scheme $E$ to scheme $C$: the length of the coherent interface increases to the size of the particles (as demonstrated in our simulations in Figure 5). As explained in section 3.4.3, the apparent “anomaly” in the mechanisms for LiFe$_{0.125}$Co$_{0.875}$PO$_4$ is due to opposing effects arising from the decrease in the change in volume during the reaction and the reduced coherency at the interface (owing to the decreasing amount of disorder resulting from reduced Co content). Therefore, even though it is possible to correlate the trends in the behavior in the mechanisms with changing substitution levels, because of the complicated interplay between lattice disruption and change in volume it is still not trivial to predict what mechanism will occur when. Nonetheless, studying the whole series has provided considerable insight into the general trends and dominant factors controlling the mechanism.

4. CONCLUSIONS

A comprehensive mechanistic study of the delithiation of the cosubstituted LiFe$_x$Co$_{1-x}$PO$_4$ materials was performed using in situ XRD. Correlations between the seemingly different mechanisms have been discussed within the cosubstituted olivines (as summarized in Figure 11), the LiFe$_{x}$Co$_{1-x}$PO$_4$ series ($0 \leq x \leq 0.95$). They are distinguished by the length of the coherent interface and whether the intermediate Li compositions (i.e., those between the fully lithiated and fully delithiated values) coexist within or between the particles. Increasing the Co substitution level increases the number of observable particles reacting via the single-phase mechanism during the plateau of the Fe$^{2+}$/Fe$^{3+}$ oxidation reaction and vice versa (i.e., Fe substitution increases the observable number of particles reacting via the single-phase mechanism during the Co$^{2+}$/Co$^{3+}$ oxidation reaction). From previous studies, we know that this is also the case when a larger current is applied. Increasing the substitution levels also allows intermediate Li compositions to exist within the particle rather than between particles (i.e., the coherent interface). It was also observed that the difference between the volumes of the two species in each transformation is important and that when there is a small difference in volume the single-phase reaction is likely to occur.

This study helps to establish how the solid solution mechanisms are related to the two-phase mechanism, how the mechanisms are affected by the varying length of the coherent interface, and how the different mechanisms can be distinguished using in situ XRD. It is key to understand how the battery electrode materials lithiate and delithiate in order to optimize current materials and provide a foundation for what characteristics future cathode materials should have (i.e., dopant and substituted materials). Critically, the formation of interfaces versus solid solutions during structural transformations can have implications for the fracturing of particles over multiple cycles: no energetically unfavorable interfaces are formed.
for a solid solution, leading to improved capacity retention. Furthermore, solid-solution mechanisms should in general lead to higher-rate materials and improved performance.

ASSOCIATED CONTENT

Supporting Information
The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.chemmater.6b00319.

The electrochemistry recorded during the in situ XRD experiments and the points in the electrochemistry at which the diffusion patterns were collected; three individual in situ XRD patterns, Rietveld refinements, and difference plots of LiFePO₄ at different states of charge; XRD patterns of LiFe₀.₃Co₀.₇PO₄ (0 ≤ x ≤ 1); SEM image of a LiFePO₄ composite electrode and particle size analysis and SEM images of as-synthesized LiCoPO₄; discharge capacities obtained during the in situ XRD studies; electrochemical data collected during the in situ XRD experiments; ex situ ⁴²¹P NMR spectra at the end of the first charge for LiFe₀.₃Co₀.₇PO₄ (0 ≤ x ≤ 1); individual XRD patterns at different states of charge for the Fe-rich materials (x = 1, 0.95, 0.875); evidence for the formation of the fully delithiated Fe₀.₃₂₅Co₀.₇₅PO₄ phase at the end of the second charge; concentration profile along the a axis of the 100 nm particle used in the simulation; XRD patterns for the first charge; the a, b, and c unit cell parameters for LiFe₀.₃Co₀.₇PO₄, Fe₀.₃Co₀.₇PO₄, Li₁₋ₓFe₀.₃Co₁₋ₓPO₄, and Li₁₋ₓFe₀.₃Co₁₋ₓPO₄ (0 ≤ x ≤ 1) as functions of Fe content; percentage change in the lattice parameters compared with LiFePO₄ for LiFe₀.₃Co₁₋ₓPO₄, Fe₀.₃Co₁₋ₓPO₄, Li₁₋ₓFe₀.₃Co₁₋ₓPO₄, and Li₁₋ₓFe₀.₃Co₁₋ₓPO₄ (0 ≤ x ≤ 1) and the a, b, and c lattice parameter variations, plotted as populations densities, as functions of scan number for all of the reactions discussed in this paper (PDF)

AUTHOR INFORMATION

Corresponding Author
E-mail: cpg27@cam.ac.uk.

Present Addresses
H.L.: X-ray Science Division, Advanced Photon Source, Argonne National Laboratory, Argonne, Illinois 60439, USA.
M.L.: Weizmann Institute of Science, Rehovot 76100, Israel.

Notes
The authors declare no competing financial interest. All the raw data for the XRD can be accessed from the University of Cambridge data repository available at the following DOI link: http://dx.doi.org/10.17863/CAM.21.

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Figure 11. Pseudophase diagram of Li₁₋ₓFeₓCo₁₋ₓPO₄ showing the evolution of the phases and the mechanisms by which they delithiate with decreasing Li content and varying Fe content (0 ≤ x, y ≤ 1). Red, green, purple, and blue represent the Li₁₋ₓ, Li₁₋ₓ₋ₓ, Li₁₋ₓ₋ₓ₋ₓ, and LiFeᵦCoᵦ₋ₓPO₄ phases, respectively, and the black, gray, and white bars represent the bulk single-phase mechanism (C), the nonequilibrium single-phase mechanism occurring particle-by-particle (D), and the two-phase mechanism with a coherent interface (E), respectively. Arrow 1 shows varying Li compositions existing within rather than between the particles (scheme D to scheme E). The direction of arrow 1 shows the change of the mechanism from the single-phase transition occurring discretely between particles to the two-phase mechanism with significant coherency at the interface. The direction of arrow 2 indicates an increase in the number of particles reacting simultaneously (scheme D to scheme C). Arrow 3 shows an increasing length of the coherent interface, i.e., a transition from scheme E to scheme D. *The end of charge for LiFe₀.₀₅Co₀.₉₅PO₄ was not collected because of limitations at the beamline, and the fully delithiated phase was not observed on the first charge for LiFe₀.₆₃Co₀.₇₅PO₄.
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