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Nucleation of Brushite and Hydroxyapatite from Amorphous Calcium Phosphate Phases Revealed by Dynamic *In Situ* Raman Spectroscopy

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ABSTRACT: Since the 1970s, it has been shown that calcium phosphate crystals nucleate from one or several early amorphous calcium phosphate phases into several *in vivo* and *in vitro* systems. However, the precise chemical composition, structure, and transformation mechanism of these amorphous phases remain controversial. Here, we characterize the reaction mechanism and kinetics of formation of two phosphate crystals, brushite and hydroxyapatite, by using *in situ* Raman spectroscopy in batch reactors at 25 °C. We investigate three pH regimes to control the phosphate speciation in solution and used solutions with or without citric acid, a complexing agent that may stabilize the amorphous phases. As expected, brushite ($CaHPO_4 \cdot 2H_2O$) forms at pH < 9.8. Amorphous calcium phosphate (ACP: $CaHPO_4 \cdot nH_2O$) with a short lifetime (<2 min) and octocalcium phosphate (OCP: $Ca_8(HPO_4)_2(PO_4)_4 \cdot 5H_2O$) are the main transient phases prior to brushite nucleation that occurs after ~8 min. At pH > 11, hydroxyapatite (HAp: $Ca_{10}(PO_4)_6(OH)_2$) nucleates after >35 min, depending on the experimental conditions. The reaction mechanism steps for hydroxyapatite are more complex compared to brushite. For hydroxyapatite formation, amorphous calcium phosphate phases with different chemical composition ($Ca(HPO_4)_{1-x}(PO_4)_{(2/3)x} \cdot nH_2O$, with x in the range 0.2−1, and with different lifetime may form. Amorphous tricalcium phosphate (ATCP: $Ca(PO_4)_{2/3} \cdot nH_2O$ or $Ca_3(PO_4)_2 \cdot nH_2O$ when $x = 1$) is the most persistent phase which can either transform into OCP and then hydroxyapatite or directly evolve into hydroxyapatite at pH > 12.2. The presence of citric acid retards the transformation kinetics by increasing the nucleation times of brushite and hydroxyapatite but has little effect on the reaction mechanism steps. Finally, this study identifies new reactive pathways that characterize the formation of amorphous calcium phosphate phases and their transformation into brushite microcrystals or hydroxyapatite nanocrystals under abiotic conditions, relevant to a wide range of technological applications and natural environments.
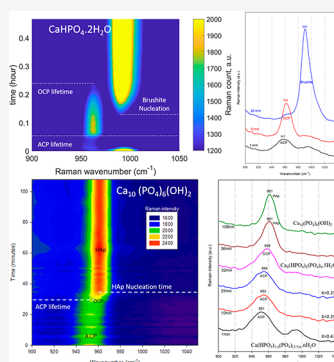
1. INTRODUCTION

Calcium phosphates (e.g., hydroxyapatite, brushite, octocalcium phosphate, and amorphous calcium phosphates) are critically important biogenic minerals constituting hard tissues (bones, teeth, and cartilages) in vertebrates. Phosphorus (P) and calcium (Ca) are also essential elements for the development of living organisms. Moreover, calcium phosphates find wide medical and industrial applications in dentistry, orthopedics, reconstructive surgery, food additives, fertilizers, and water depollution.[1−6] The formation of calcium phosphates and the interactions and associations of these minerals with organic macromolecules have been widely investigated under *in vivo* and *in vitro* conditions in the last decades[7−10] in order to identify the nature of the first primary precipitating particles, their lifetime, and their chemical transformation into other minerals in aqueous media.[11−20] For example, the formation of hydroxyapatite nanocrystals ($Ca_{10}(PO_4)_6(OH)_2$) under biotic or abiotic conditions involves the early formation of a transient amorphous calcium phosphate phase (ACP).[11−26] This phase may either (1) transform directly by a solid-state transformation, (2) dissolve

and reprecipitate to produce nanocrystalline hydroxyapatite, or (3) nucleate inside other amorphous phases (e.g., refs 9, 11, 16, 18, and 24). The first theory of phosphate formation from precursor amorphous phases was proposed by Posner and Betts[11] who observed prenucleation clusters of $Ca_9(PO_4)_6$ with a size close to ~1 nm (so-called "Posner's cluster"). These authors proposed that the clusters not only could be the building blocks for ACP but also could play an important role during the transformation of ACP into hydroxyapatite, suggesting that ACP only dissociates into these clusters rather than undergoing a complete ionic dissolution.[11,16] However, the structure of prenucleation clusters during hydroxyapatite formation is still debated (e.g., refs 12, 13, 25, and 26). For example, crystalline metastable phases such as octocalcium
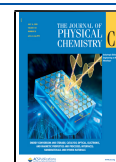
Table 1. List of Dynamic *In Situ* Raman Spectroscopy Experiments Performed to Study the Nucleation of Brushite and Hydroxyapatite[a]

expt.	temp (°C)	pH regime	expt. duration (h)	citric acid	transient phase(s) and principle Raman peak	final mineral phase(s) and principle Raman peak
1	25	from 9.8 to 6.8	23	none	ACP at 957 cm^{-1}	brushite at 990 cm^{-1}
					OCP at 962 cm^{-1}	
2	25	from 9.8 to 6.8	18	yes	ACP at 955 cm^{-1}	brushite at 990 cm^{-1}
					OCP at 962 cm^{-1}	hydroxyapatite at 963 cm^{-1} (minor proportion)
3	24	pH > 12.2	19	none	ACP at 954 cm^{-1}	hydroxyapatite at 963 cm^{-1}
					ATCP at 943 cm^{-1}	ATCP and OCP (minor proportions)
					OCP at 961 cm^{-1}	
4	25	pH > 12.2	20	yes		hydroxyapatite at 963 cm^{-1}
					ACP at 956 cm^{-1}	ATCP (significant proportion)
					ATCP at 943 cm^{-1}	OCP (minor proportion)
					OCP at 961 cm^{-1}	
5	24	from 12.4 to 11	2	none	ACP1 at 951 cm^{-1}	hydroxyapatite at 962 cm^{-1}
					ACP2 at 954 cm^{-1}	
					OCP at 959 cm^{-1}	

[a]Experiments were performed under three different pH regimes, equimolar Ca/P ratio or hydroxyapatite stochiometric ratio (Ca/P = 1.66), and two different calcium sources (CaCl$_2$ and Ca(OH)$_2$).

phosphate (OCP) (Ca$_8$(HPO$_4$)$_2$(PO$_4$)$_4$·5H$_2$O) and brushite (CaHPO$_4$·2H$_2$O) have been proposed to form as transient phases prior to hydroxyapatite (HAp) nucleation. Therefore, a convincing temporal and/or spatial characterization of phosphate formation in natural or synthetic samples is still lacking (e.g., refs 5, 8, 15, 27, and 28) despite the use of sophisticated time-resolved measurements and simulations performed in the last two decades, such as *in situ* X-ray absorption (XAS), *in situ* small/wide-angle X-ray scattering (SAXS/WAXS), electron transmission microscopy (cryo-TEM or liquid-cell TEM), atomic force microscopy (liquid-cell AFM), and *ab initio* numerical simulations based on the density functional theory (e.g., refs 1, 12, 13, 19, 25–27, 29, and 30). Despite all these available techniques, more knowledge is required to understand how phosphate minerals nucleate and grow from solutions and slurries. In this context, time-resolved Raman spectroscopy measurements provide invaluable information on the nucleation, transformation, and growth of particles and crystals, as recently demonstrated for several carbonates[31–33] and phosphates minerals.[34–37] This spectroscopy technique allows discriminating between amorphous and crystalline phases that form early during the nucleation and growth of more stable minerals.

In the present study, the nucleation of brushite and hydroxyapatite was monitored in real-time and *in situ* by using Raman spectroscopy at 25 °C. For both minerals, amorphous calcium phosphate (Ca(HPO$_4$)$_{1-x}$(PO$_4$)$_{(2/3)x}$·nH$_2$O) with different Raman signature instantaneously formed as ionic solutions were rapidly mixed under mechanical stirring. Then, the amorphous phases transformed rapidly or slowly into OCP (crystalline transient phase). Finally, OCP transformed into brushite microcrystals or into hydroxyapatite nanocrystals depending on the experimental investigated conditions. We varied the pH, the HPO$_4^{2-}$/PO$_4^{3-}$ ratio, and the Ca/P ratio. The lifetime of amorphous and crystalline transient phases, reaction mechanisms, and kinetics of formation of brushite and hydroxyapatite were then measured. We acquired several *ex situ* measurements and images of the products recovered at the end of the experiments in order to characterize the average particles size, crystal shape, and mineral composition.

2. MATERIALS AND METHODS

2.1. Time-Lapse Raman Spectroscopy. The formation of brushite and hydroxyapatite was monitored using a Raman probe (785 nm infrared laser) immersed into a C22 Hastelloy batch reactor with internal volume of 600 mL. This experimental setup is described in a previous study.[31] Raman spectra were collected with an exposure time of 3 or 2 s and averaged over 3 or 2 scans. The delay between successive acquisitions varied between 15 s and 1 h, depending on the investigated reaction. The duration of experiments was arbitrarily imposed from 2 to 24 h, and all collected spectra were saved on the control computer.

Selected Raman peaks (strongest peak) corresponding to identified mineral phases (see Table S1 and Table 1) were fitted by using simple or combined Gaussian models in order to calculate the peak full width at half-maximum (fwhm) and the integrated peak surface area as a function of time (Movie S1). The Raman signals were fitted using the following procedure. First, we selected a small region of the entire Raman spectrum that contained only the peaks relevant for the reaction studied. Then, the baseline was removed to correct for temporal fluctuations of the intensity of the signal. Finally, we decomposed the Raman signal into two, three, or four Gaussian curves, depending on the number of species present in the system. For each species, the position of the peak was fixed, and the amplitude and standard deviation of each Gaussian were fitted using a nonlinear least-squares method (Movies S1, S2, and S3). This calculation provides the peak decomposition necessary to propose relevant reaction mechanisms and to quantify the kinetics of formation of calcium phosphates phases in aqueous solutions or slurries, including nucleation time and lifetime of minerals and aqueous species.

2.2. Brushite (CaHPO$_4$·2H$_2$O) from a Phosphate Solution. Two hundred milliliters of phosphate solution (0.2 M of Na$_2$HPO$_4$, pH ~ 9.8) was first placed in the reactor under continuous stirring (400 rpm) at a temperature of ~25 °C. Raman spectroscopy monitoring reveals a strong peak at 993 cm^{-1}, characteristic of HPO$_4^{2-}$, before the addition of a calcium solution (Figure S1a). Then, 200 mL of calcium
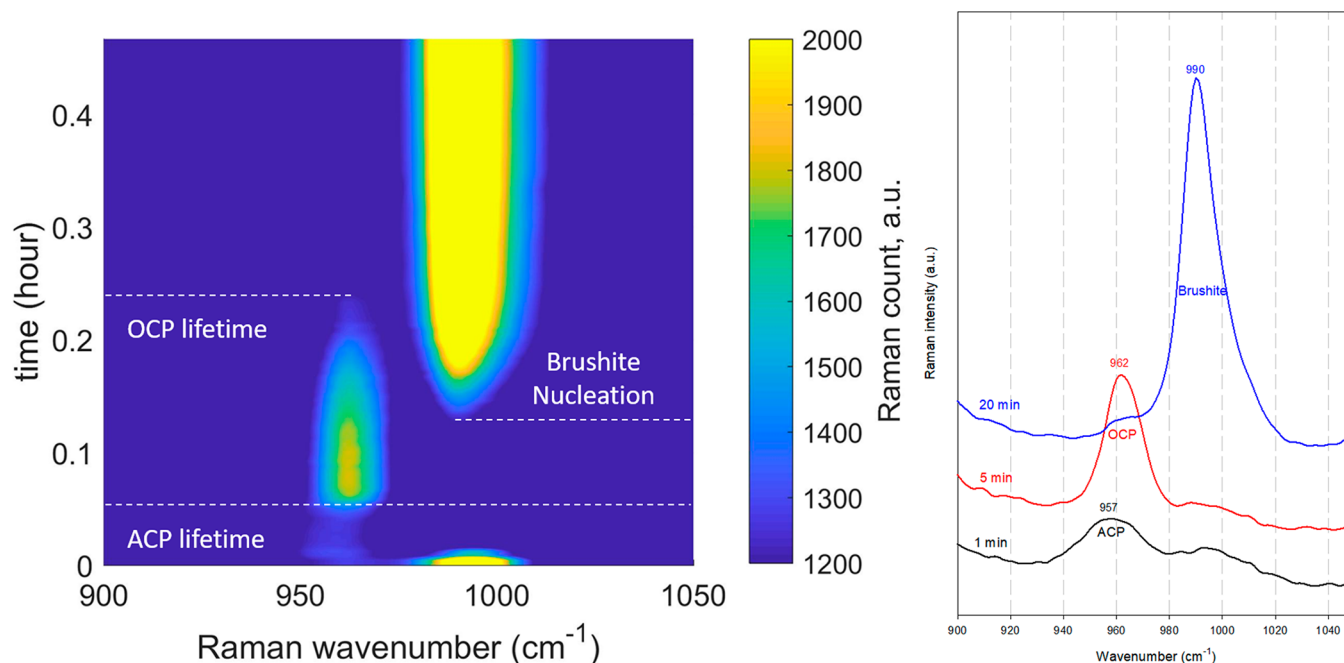
Figure 1. (Left) Time-lapse Raman spectroscopy monitoring of the formation of brushite in experiment 1 (Table 1). (Right) Main peaks of transient phases (ACP and OCP) and brushite, the most stable phosphate phase under the investigated conditions.

solution (0.2 M of $CaCl_2$, pH $\sim$ 6.8) was rapidly added into the system with a syringe for about 1−2 min leading to the instantaneous formation of a gel-like amorphous calcium phosphate phase with a Raman peak at 957 cm^{-1} (Figure S1b). The chemical transformation of this amorphous phase to crystalline phases was then monitored for 23 h with an acquisition frequency of 1 Raman spectrum every 15 s during the first 20 min and every 1 or 5 min in the remaining time. The same experiment was performed in presence of 1 g of citric acid ($C_6H_8O_7$), initially dissolved in the calcium solution in order to assess the effect of this acid on the kinetics and reaction mechanism. The citric acid is used here as a complexing agent that is expected to stabilize transient amorphous phosphate phases for longer durations than without acid. All chemical reactants with high purity (>99%) were provided by Sigma-Aldrich.

**2.3. Hydroxyapatite from Na_2HPO_4−$Ca(OH)_2$ Slurry.** Two hundred milliliters of deionized water (18.2 MΩ of resistivity) and 3 g of $Ca(OH)_2$ (>96% of purity provided by Sigma-Aldrich) were placed in the reactor under continuous stirring (400 rpm) at a temperature of $\sim$25 °C. Direct Raman spectroscopy monitoring reveals a peak at 362 cm^{-1}, characteristic of calcium hydroxide, before the addition of a phosphate solution (Figure S2). After the addition of 200 mL of a phosphate solution (0.2 M of Na_2HPO_4, pH $\sim$ 9.8), the calcium hydroxide progressively dissolves (Figure S2) while hydroxyapatite forms under an alkaline pH higher than 12, constrained by the release of OH$^-$ ions, as shown in the following overall reaction:

$$10Ca(OH)_2 + 6HPO_4^{2-}$$
$$\Rightarrow Ca_{10}(PO_4)_6(OH)_2 + 12OH^- + 6H_2O \qquad (1)$$
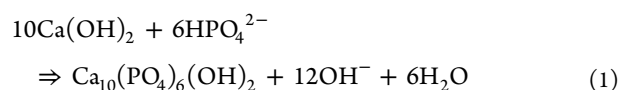
This overall reaction involves the formation of amorphous and crystalline transient phases that were monitored in real-time by Raman spectroscopy for 18 h with an acquisition frequency of 1 Raman spectrum every 15 s during the first 20 min and every

1 or 5 min in the remaining time. The same experiment was performed in presence of 1 g of citric acid ($C_6H_8O_7$), initially dissolved in the calcium hydroxide slurry

2.4. Hydroxyapatite from Ionic Solutions. Two hundred milliliters of phosphate solution (0.2 M of PO_4^{3-}/ HPO_4^{2-}, pH $\sim$ 12.4 adjusted with NaOH) was first placed in the reactor under continuous stirring (400 rpm) at a temperature of $\sim$25 °C. Direct Raman spectroscopy monitoring confirms the presence of peaks for HPO_4^{2-} at 992 cm^{-1} and PO_4^{3-} at 939 cm^{-1}, before the addition of a calcium solution (Figure S3a). Then, 200 mL of calcium solution (0.33 M of $CaCl_2$) was rapidly added into the system with a syringe for about 1−2 min. Similar to the brushite experiment, the fast mixing of these two ionic solutions led to the instantaneous formation of a gel-like phase that contained an amorphous calcium phase with a Raman peak at 951 cm^{-1} (Figure S3b). The lifetime and chemical transformation of this gel into crystalline phases were monitored in real-time for 23 h with an acquisition frequency of 1 Raman spectrum every 15 s during the first 20 min and every 1 or 5 min in the remaining time. The overall reaction to form hydroxyapatite can be written as follows:

$$2HPO_4^{2-} + 4PO_4^{3-} + 2OH^- + 10Ca^{2+}$$
$$\Rightarrow Ca_{10}(PO_4)_6(OH)_2 + 2H^+ \qquad (2)$$
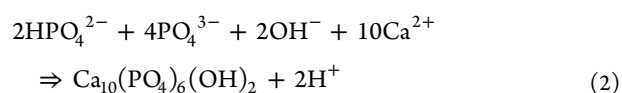
In contrast to the formation of hydroxyapatite from a calcium hydroxide slurry (reaction 1), the synthesis of hydroxyapatite using ionic solutions releases protons, which produces a decrease of pH during the experiment from $\sim$12.4 to $\sim$11.

In summary, three different pH regimes were investigated in this study using an equimolar Ca/P ratio or hydroxyapatite stochiometric ratio (Ca/P = 1.66) and two different Ca sources ($CaCl_2$ and $Ca(OH)_2$). The pH in the solutions and slurries was systematically measured at the beginning and the end of each experiment. We used a conventional pH meter (Mettler Toledo MA235). However, the *in situ* pH variations
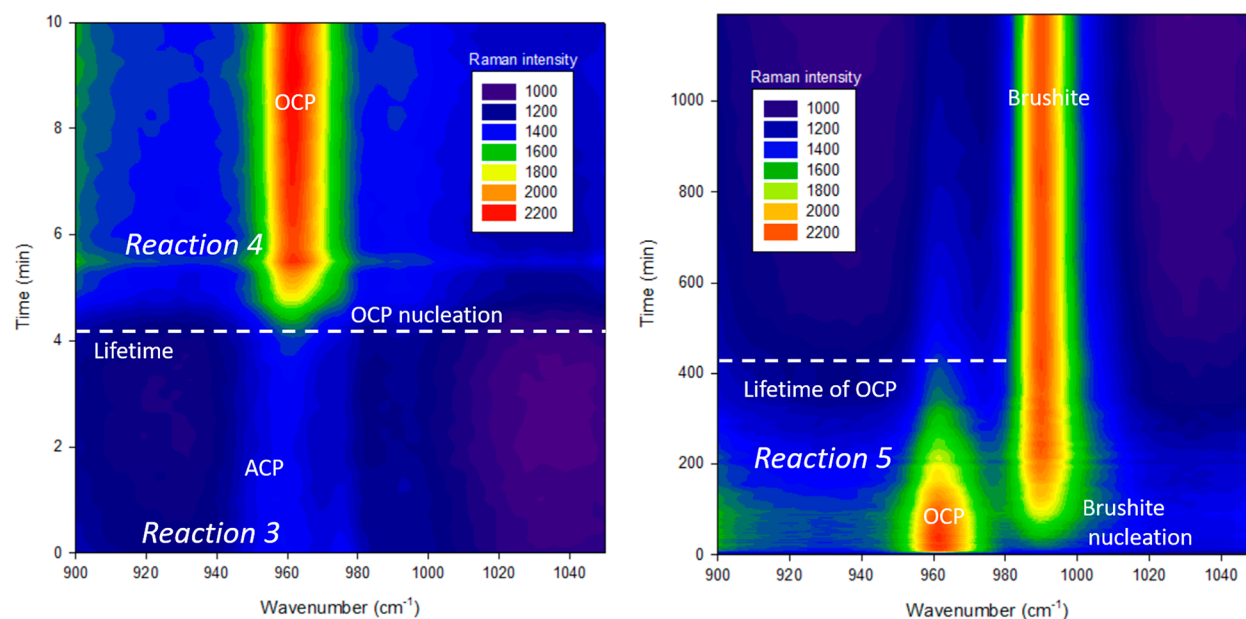
Figure 2. Time-lapse Raman spectroscopy monitoring of the formation of brushite in experiment 2 (Table 1). (Left) Raw data Raman spectra between 0 and 10 min showing the formation of ACP (reaction 3 in the text) and the nucleation time of OCP (reaction 4 in the text). (Right) Raw data Raman spectra from 0 to 1200 min showing the transformation of OCP into brushite (reaction 5 in the text).

during precipitation experiments were not recorded. Table 1 summarizes all experiments performed in the present study. Each experiment was repeated at least three times to verify the reproducibility of the results.

2.5. *Ex Situ* Characterization of Precipitates. At the end of each experiment, the solid product was recovered by centrifugation and washed twice with ultrapure water and once with ethanol. Then, it was dried at 60 °C for 48 h. The dry solid products were stored in plastic flasks for subsequent characterization of selected samples by field emission gun scanning electron microscopy (FESEM) and powder X-ray diffraction (XRD).

For high-resolution imaging, the solid products were dispersed by ultrasonic treatment in absolute ethanol for 5–10 min. One or two droplets of the suspension were then deposited directly on an aluminum support and coated with gold and platinum. The morphology of the crystals was imaged using a Zeiss Ultra 55 field emission gun scanning electron microscope (FESEM) with a maximum spatial resolution of approximately 1 nm at 15 kV.

XRD analyses were performed using a Siemens D5000 diffractometer in the Bragg–Brentano geometry, equipped with a theta–theta goniometer with a rotating sample holder. The XRD patterns were collected using Cu $k\alpha_1$ ($\lambda_{k\alpha1}$ = 1.5406 Å) and $k\alpha_2$ ($\lambda_{k\alpha2}$ = 1.5444 Å) radiations in the range 2θ = 10–70° with a step size of 0.04° and a counting time of 6 s per step.

3. RESULTS AND DISCUSSION

3.1. Brushite Formation: Reaction Mechanism and Kinetics. The quick mixing of two equimolar ionic solutions, one containing HPO_4^{2-} (0.2 M, pH ∼ 9.8) and the other containing Ca^{2+} (0.2 M, pH ∼ 6.8), leads the instantaneous formation of an amorphous calcium phosphate (ACP: $CaHPO_4 \cdot nH_2O$) with a peak at 957 cm^{-1} (Figure S1b). This Raman signature is transient with a lifetime of about 2 min. Then, ACP transforms into octocalcium phosphate (OCP:

$Ca_8(HPO_4)_2(PO_4)_4 \cdot 5H_2O$) with a peak at 962 cm^{-1}. This crystalline phase nucleates from ACP after 2 min, and its maximum Raman intensity is reached after 5 min. The OCP is also a transient phase that progressively transforms into brushite ($CaHPO_4 \cdot 2H_2O$), with a peak at 990 cm^{-1}, after a nucleation time of 7.5 min. Brushite reaches a maximum Raman intensity after 24 min. The progressive increase of the brushite Raman peak is proportional to the decrease of the OCP Raman intensity until the total consumption of OCP. This sequence of reactions and kinetics is summarized in Figure 1, Figure S4, and Movie S1. Based on these data, the following reaction mechanism is proposed.

1. Instantaneous formation of ACP:

$$HPO_4^{2-} + Ca^{2+} + nH_2O \Rightarrow CaHPO_4 \cdot nH_2O \quad (3)$$
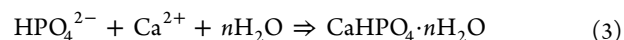
Amorphous calcium phosphate containing only HPO_4^{2-} (Ca/P = 1) is assumed at this investigated pH regime where only HPO_4^{2-} ions may exist in solution. However, the incorporation of phosphate into the amorphous phase ($Ca(HPO_4)_{1-x}(PO_4)_{(2/3)x} \cdot nH_2O$) and the removal of protons (H^+) at the solid–fluid interface are not excluded.

2. Transformation of ACP into OCP via a solid-state crystallization pathway:

$$8CaHPO_4 \cdot nH_2O + 5H_2O$$
$$\Rightarrow Ca_8(HPO_4)_2(PO_4)_4 \cdot 5H_2O + 2H_2PO_4^- + 2H^+$$
$$+ 8nH_2O \quad (4)$$
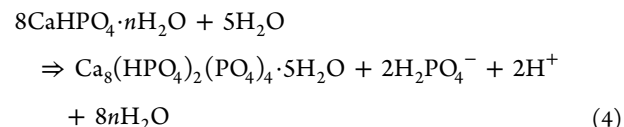
This reaction implies the protonation of residual phosphate ions as confirmed by the peaks at 880 and 1080 cm^{-1} assigned to $H_2PO_4^-$ (Figure S5 and Table S1). This means that a significant decrease of pH (probably, pH < 6.7) takes place in first minutes that favor then the OCP transformation into brushite as directly monitored by Raman spectroscopy (Figure 1) and described below by reaction 5.
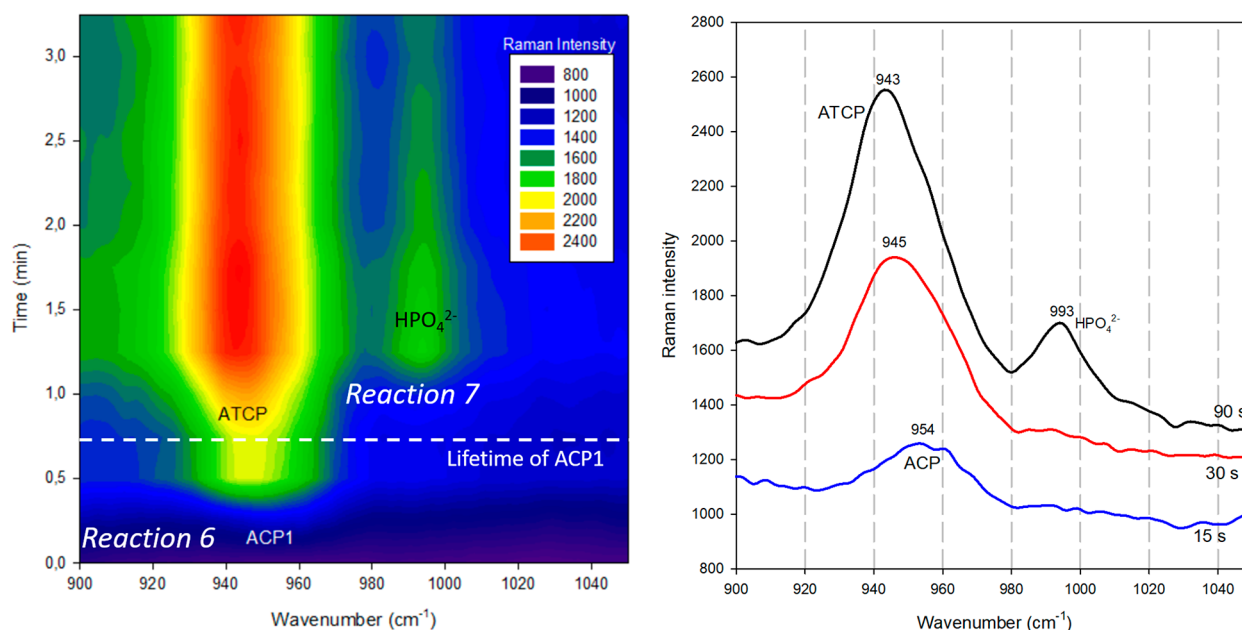
Figure 3. Time-lapse Raman spectroscopy monitoring of the formation of hydroxyapatite (HAp) in experiment 3 (Table 1). (Left) Raw data Raman spectra between 0 and 3 min indicating the formation of ACP1 (reaction 6 in the text) and the transformation of ACP1 into ATCP (reaction 7 in the text). (Right) Three raw data Raman spectra at 15, 30, and 90 s showing a fast shift of the position of the Raman peak of amorphous phases from 954 to 943 cm^{-1}.

In addition, a solid-state crystallization is assumed because the overall transformation of ACP into OCP takes place abruptly in less than 15 s, which corresponds to the time resolution in our experiments, as illustrated in Figure 1.

3. Transformation of OCP into brushite via a dissolution–recrystallization pathway:

$$Ca_8(HPO_4)_2(PO_4)_4 \cdot 5H_2O + 2H_2PO_4^- + 2H^+ + 11H_2O$$

$$\Rightarrow 8CaHPO_4 \cdot 2H_2O \tag{5}$$
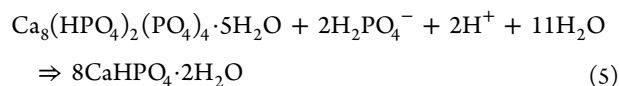
The dissolution–recrystallization pathway is here assumed because the OCP transient phase is progressively consumed by the formation and growth of brushite (Figure 1). This interpretation is supported by a temporal increase in the fwhm of the main OCP Raman peak until its total consumption (Figure S6). This result can be interpreted by an average decrease of the crystals size, z, of OCP with $z \, \alpha \, 1/$fwhm$_{OCP}$, due to a progressive dissolution process. Conversely, the temporal decrease of fwhm for brushite formation indicates a crystal growth process.

Ex situ characterization of solids recovered at the end of experiments by FESEM and XRD confirmed the presence of elongated microcrystals (>20 μm) of brushite (see Figure S7).

In the presence of citric acid, the reaction mechanism remains very similar because the reactions 3−5 occur, and the only measurable difference is a very slight transformation of brushite into hydroxyapatite confirmed by XRD in the recovered solid product (experiment 2 in Table 1 and Figure S8). In presence of citric acid, the transformation kinetics, and mainly the transformation of OCP into brushite (reaction 5), are significantly retarded from 15 (Figure 1) to 400 min (Figure 2). Conversely, the formation of ACP (reaction 3) and the transformation of ACP into OCP (reaction 4) are only slightly retarded, as displayed in Figure 2.

3.2. Hydroxyapatite Formation from Ca(OH)$_2$ Slurry: Reaction Mechanism and Kinetics. In this case, a

phosphate ionic solution (0.2 M of HPO$_4^{2-}$, pH ~ 9.8) was rapidly added to a Ca(OH)$_2$ slurry (0.015 g/g$_{H2O}$, pH ~ 12.2). As expected, an amorphous calcium phosphate (ACP1) with a peak at 954 cm^{-1} forms instantaneously in the first 15 s and has a lifetime of less than 1 min. The ACP1 rapidly transforms into another amorphous calcium phase with a peak at 943 cm^{-1} (ACP2), a transformation accompanied by a transient release of HPO$_4^{2-}$ ions with a peak at 993 cm^{-1} (Figure 3). Based on this result, we assume that the shift of the peak position of the calcium amorphous phases is exclusively related to the HPO$_4^{2-}$ or PO$_4^{3-}$ structural content into the amorphous phase (Ca(HPO$_4$)$_{1-x}$(PO$_4$)$_{(2/3)x}$·nH$_2$O, with x that varies between 0 and 1. Therefore, the calcium amorphous phase can show a Raman signature with broad peaks between 943 cm^{-1} for Ca$_3$(PO$_4$)$_2$·nH$_2$O (ATCP) and 957 cm^{-1} for CaHPO$_4$·nH$_2$O (ACP). This result is illustrated in Figure S9, where the parameter x can be calculated by a linear interpolation of the peak position in the interval 943−957 cm^{-1} ($x = 68.357 − (1/14) \times P_{ACP}$, where P_{ACP} is the position in cm^{-1} comprised between 943 and 957). Then, the ATCP slowly transforms into hydroxyapatite with a peak at 963 cm^{-1}. The OCP clearly detected in the brushite systems as a transient phase (experiments 1 and 2) is also expected to form in more alkaline systems. However, the strongest Raman peak of OCP (962 cm^{-1}) is very close to the main peak of hydroxyapatite (963 cm^{-1}). For this reason, the OCP-like layers transient phase is also considered in the deconvolution peak fitting, as illustrated in the Movie S2 and in the kinetics behavior summarized in Figure S10. Note that the OCP-like layers formation in this particular case remains speculative because we did not detect this phase in the solid product after the experiment. However, we needed this phase to fit the Raman data. Based on these time-resolved Raman spectroscopy measurements, the following reaction mechanism is suggested.
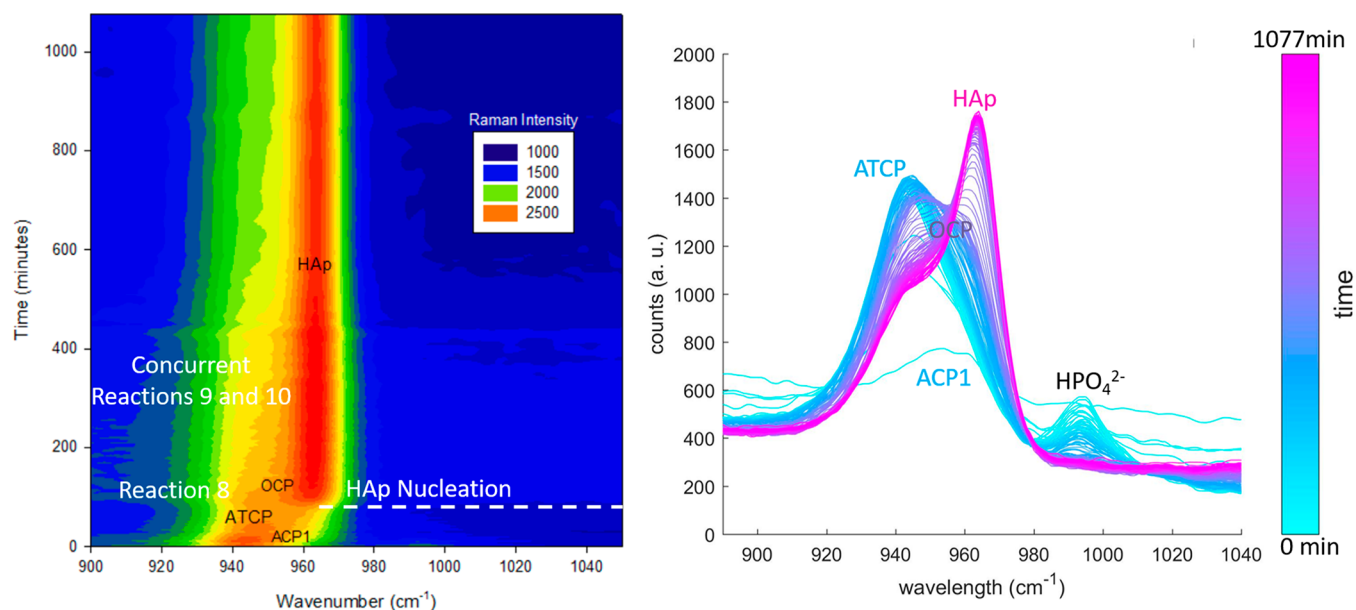
1. Instantaneous formation of ACP1:

Figure 4. Time-lapse Raman spectroscopy monitoring of the formation of hydroxyapatite (HAp) in experiment 3 (Table 1). (Left) Raw data Raman spectra between 0 and 1077 min showing the transformation of ATCP into OCP (reaction 8 in the text) and the synchronous transformations of OCP into hydroxyapatite (reaction 9 in the text) and ATCP into hydroxyapatite (reaction 10 in the text). (Right) Time-lapse evolution of the main peaks used for deconvolution fitting.
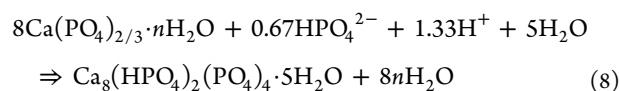
$$HPO_4^{2-} + Ca^{2+} + nH_2O$$
$$\Rightarrow Ca(HPO_4)_{0.8}(PO_4)_{0.13} \cdot nH_2O + 0.07PO_4^{3-} + 0.2H^+ \qquad (6)$$
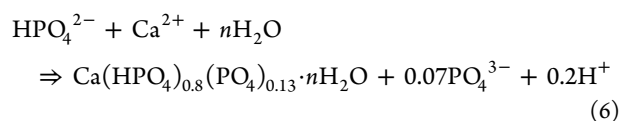
Here, we assume that the produced protons (H^+) are instantaneously neutralized by the calcium hydroxide dissolution ($Ca(OH)_2 \Rightarrow Ca^{2+} + 2OH^-$) such that a high-alkaline pH (>12.2) is maintained during the experiment as expected by overall reaction 1 (see the section Materials and Methods)

2. Transformation of ACP1 into ATCP via a solid-state transformation pathway:

$$Ca(HPO_4)_{0.8}(PO_4)_{0.13} \cdot nH_2O$$
$$\Rightarrow Ca(PO_4)_{2/3} \cdot nH_2O + 0.27HPO_4^{2-} + 0.53H^+ \qquad (7)$$
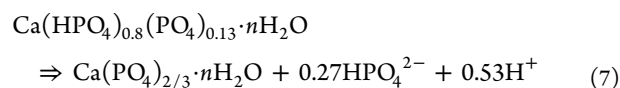
Solid-state transformation is assumed because ACP1 has a short lifetime, less than 1 min, and its transformation into ATCP takes place abruptly, as shown in Figure 3. The phase $Ca(PO_4)_{2/3} \cdot nH_2O$ is equivalent to $Ca_3(PO_4)_2 \cdot nH_2O$ reported in the literature and is constituted mainly by the so-called Posner's clusters $Ca_9(PO_4)_6$ with ~1 nm size.[11] The reaction 7 implies a release of HPO_4^{2-} ions and protons (H^+) that are also detected by Raman spectroscopy (Figure 3). These ions rapidly react to form OCP as illustrated in the following reaction, and residual phosphate ions are transformed to PO_4^{3-}, the main phosphate aqueous species in high-alkaline aqueous media. Residual protons (H^+) are neutralized to water ($H^+ + OH^- \Rightarrow H_2O$).

3. Transformation of ATCP to OCP-like layers:

$$8Ca(PO_4)_{2/3} \cdot nH_2O + 0.67HPO_4^{2-} + 1.33H^+ + 5H_2O$$
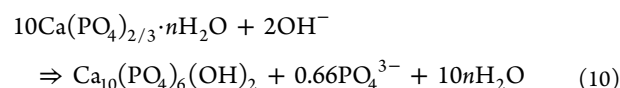$$\Rightarrow Ca_8(HPO_4)_2(PO_4)_4 \cdot 5H_2O + 8nH_2O \qquad (8)$$

As indicated above, only OCP-like layers were suspected in the raw Raman data, but it is necessary to improve the deconvolution fitting, particularly in the first 90 min (see Figure S10 and Movie S2). Moreover, the ATCP phase has a long lifetime and coexists with hydroxyapatite until the end of the experiment. For this reason, two different mechanisms may occur simultaneously to form hydroxyapatite in high-alkaline media.

4a. Transformation of OCP-like layers into hydroxyapatite:

$$Ca_8(HPO_4)_2(PO_4)_4 \cdot 5H_2O + 2Ca^{2+} + 2OH^-$$
$$\Rightarrow Ca_{10}(PO_4)_6(OH)_2 + 2H^+ + 5H_2O \qquad (9)$$
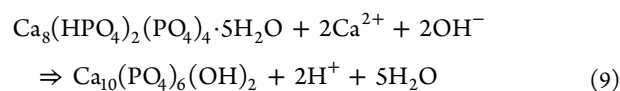
4b. Transformation of ATCP into hydroxyapatite:

$$10Ca(PO_4)_{2/3} \cdot nH_2O + 2OH^-$$
$$\Rightarrow Ca_{10}(PO_4)_6(OH)_2 + 0.66PO_4^{3-} + 10nH_2O \qquad (10)$$

Both reactions 9 and 10 participate in the formation of hydroxyapatite, as shown by the temporal behavior of the Raman intensity of selected peaks (Figure 4) and the integrated peak surface areas of concerned phases (Figure S10 and Movie S2). However, the low temporal variation of the fwhm parameter (Figure S11) does not allow to conclude if the reactions take place via a dissolution–recrystallization pathway, as clearly deduced for the brushite system. In this case, partial dissolution, i.e., conserving $Ca_9(PO_4)_6$ clusters of ~1 nm size as building primary units, combined with self-assembly aggregation could operate to form hydroxyapatite, as suggested in previous studies.[11,12,14,16,18] Unfortunately, Raman dynamic *in situ* monitoring cannot provide clear or complementary information on this specific important interfacial process.

Ex situ characterization of solids recovered after the experiments by FESEM and XRD confirm the presence of acicular nanocrystals of hydroxyapatite, with size <100 nm and, probably, some residual amorphous calcium phosphate, as attested by the presence of very fine particles with size <20 nm (Figure S12).

Concerning the effect of citric acid, Raman data reveal that the reaction mechanism remains very similar because the
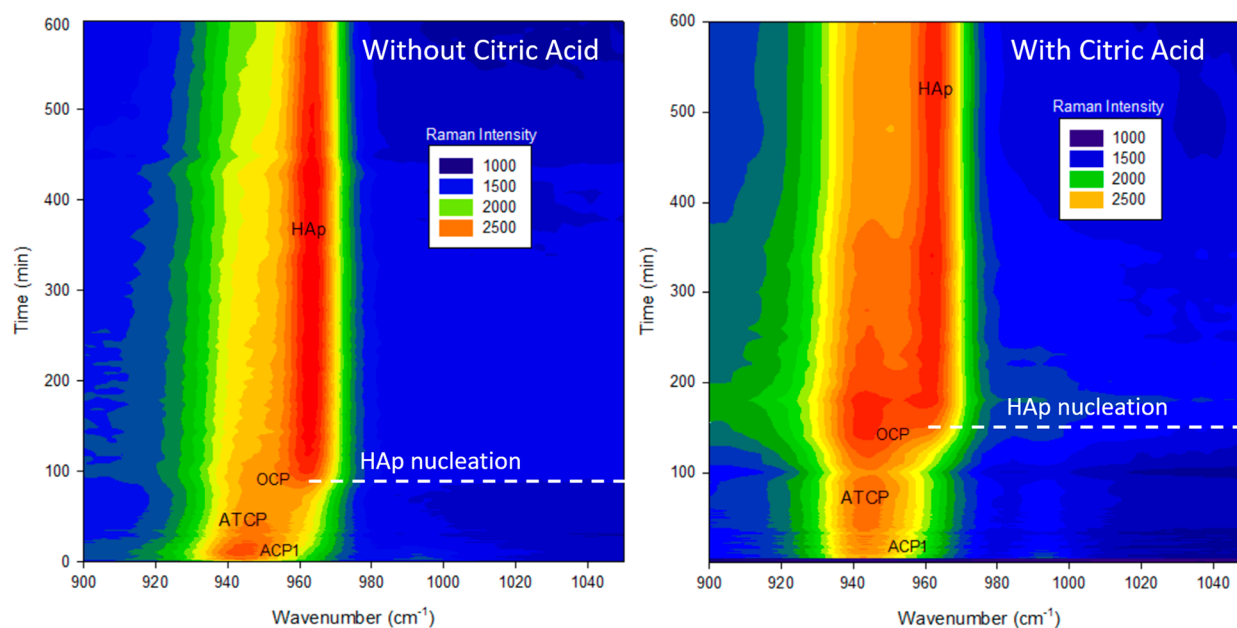
Figure 5. Time-lapse Raman spectroscopy monitoring of the formation of hydroxyapatite (HAp) in experiments 3 and 4 (Table 1). (Left) Raw data Raman spectra between 0 and 600 min show the main transient calcium phosphate phases detected during hydroxyapatite formation in experiment 3. The reaction mechanism is summarized by reactions 6–10 in the text. (Right) Raw data Raman spectra between 0 and 600 min showing the main transient calcium phosphate phases detected during hydroxyapatite formation in experiment 4 in the presence of citric acid. The reaction mechanism is very similar to that without citric acid; however, a significant retarding effect is measured as indicated by the difference of hydroxyapatite nucleation time with and without citric acid.
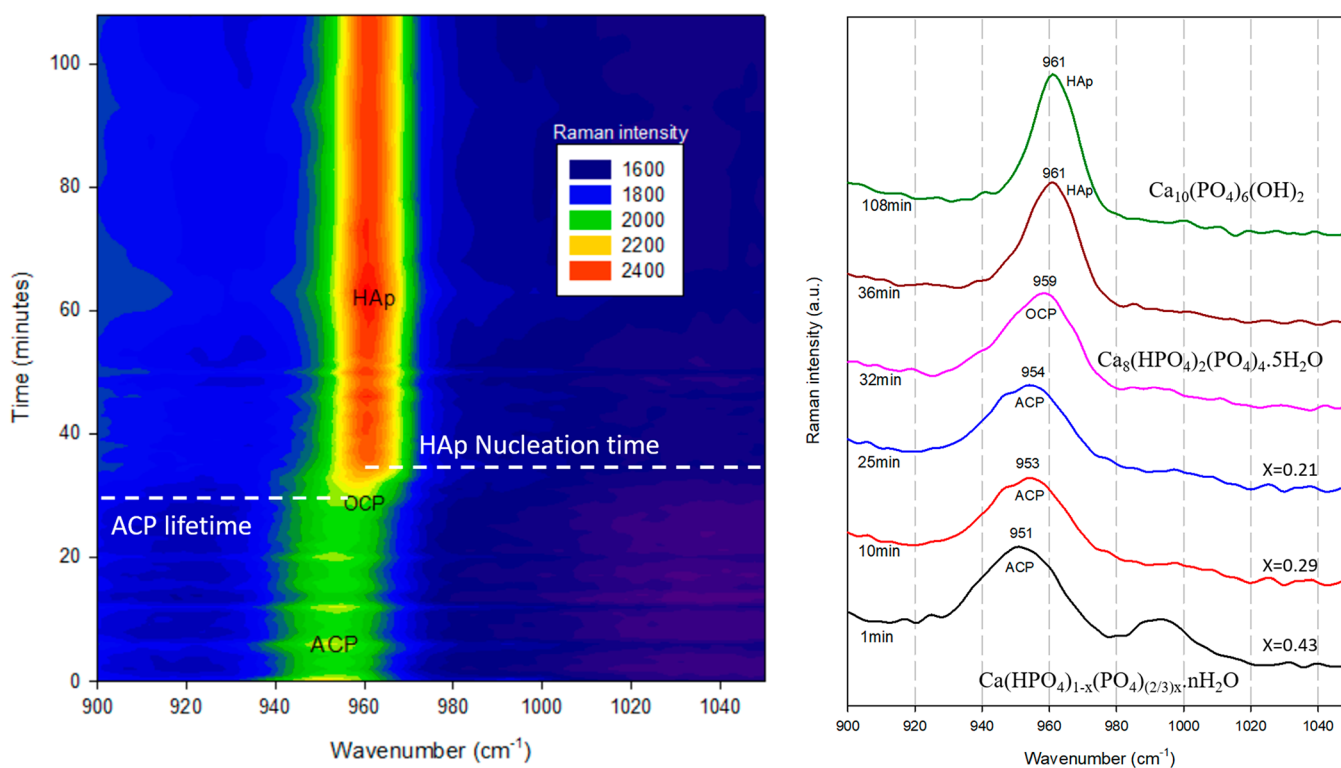

Figure 6. Time-lapse Raman spectroscopy monitoring of the formation of hydroxyapatite (HAp) in experiment 5 (Table 1). (Left) Raw data Raman spectra between 0 and 108 min indicating the lifetime of ACP and nucleation time of hydroxyapatite. (Right) Six raw data Raman spectra at 1, 10, 25, 32, 36, and 108 min showing the signatures of ACP, OCP, and hydroxyapatite. As presented in Figure S9, the phosphate content, x, was calculated using a linear interpolation ($x = 68.357 - (1/14) \times P_{ACP}$, where P_{ACP} is the position of the Raman peak in cm^{-1} comprised between 943 and 957).
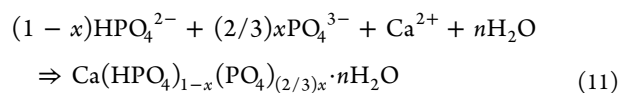
reactions 6–10 can be confirmed. The main difference concerns reaction 6 where the transient amorphous calcium

carbonate (ACP1) has a Raman signature at 957 cm^{-1} and therefore contains only HPO_4^{2-} in its structure ($CaHPO_4$·

nH$_2$O), as illustrated in Figure S9. The other difference is that the transformation kinetics of transient phases into hydroxyapatite, including the nucleation time (reactions 8−10), are significantly retarded, as illustrated in Figure 5. Conversely, the formation of ACP1 (reaction 6) and the transformation of ACP1 to ATCP (reaction 7) are slightly retarded only.
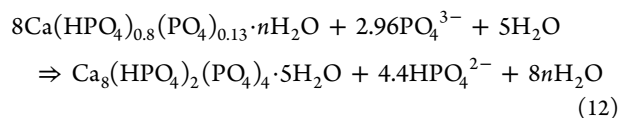
3.3. Hydroxyapatite Formation from Mixture of Ionic Solutions: Reaction Mechanism and Kinetics. The quick mixing of two ionic solutions with hydroxyapatite stochiometric ratio, Ca/P = 1.66, one containing 0.2 M of PO$_4^{3-}$/HPO$_4^{2-}$ (pH ~ 12.4 adjusted with NaOH) and the other containing Ca^{2+} (0.33M, pH ~ 6.8), leads to the instantaneous formation of amorphous calcium phosphate (ACP: Ca(HPO$_4$)$_{1-x}$(PO$_4$)$_{(2/3)x}$·nH$_2$O, x = 0.43) with a peak at 951 cm^{-1} (Figure 6). This Raman signature is transient with a short lifetime of 3−4 min. The total lifetime of ACP is about 30 min, and the position of its Raman peak varies from 951 cm^{-1} (x = 0.43) to 954 cm^{-1} (x = 0.21) prior to its transformation into OCP. Then, OCP is transformed into hydroxyapatite with a nucleation time of 36 min (Figure 6). This result is supported by the deconvolution fitting of selected Raman peaks (Figure S13 and Movie S3). The formation of OCP-like layers in this case remains speculative but in agreement with the literature.[5,27,28] Based on these time-resolved Raman spectroscopy measurements, the following reaction mechanism steps are proposed.
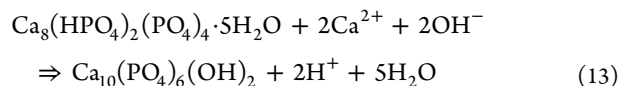
1. Instantaneous formation of ACP:

$$(1 - x)\text{HPO}_4^{2-} + (2/3)x\text{PO}_4^{3-} + \text{Ca}^{2+} + n\text{H}_2\text{O}$$
$$\Rightarrow \text{Ca}(\text{HPO}_4)_{1-x}(\text{PO}_4)_{(2/3)x}\cdot n\text{H}_2\text{O} \tag{11}$$

Here, x varies between 0.43 and 0.21; i.e., the ACP is structurally enriched with HPO$_4^{2-}$ as a function of time prior to its transformation into OCP-like layers. Clusters aggregation process combined with partial dissolution could be the responsible for this variation of phosphate content into ACP.

2. Transformation of ACP into OCP-like layers:

$$8\text{Ca}(\text{HPO}_4)_{0.8}(\text{PO}_4)_{0.13}\cdot n\text{H}_2\text{O} + 2.96\text{PO}_4^{3-} + 5\text{H}_2\text{O}$$
$$\Rightarrow \text{Ca}_8(\text{HPO}_4)_2(\text{PO}_4)_4\cdot 5\text{H}_2\text{O} + 4.4\text{HPO}_4^{2-} + 8n\text{H}_2\text{O} \tag{12}$$

A solid-state transformation is proposed because the transformation of ACP into OCP-like layers takes place over a short duration, in less than 2 min, and the position of the Raman peak shifts rapidly from 954 to 959 cm^{-1} (Figure 6).

3. Transformation of OCP-like layers into hydroxyapatite:

$$\text{Ca}_8(\text{HPO}_4)_2(\text{PO}_4)_4\cdot 5\text{H}_2\text{O} + 2\text{Ca}^{2+} + 2\text{OH}^-$$
$$\Rightarrow \text{Ca}_{10}(\text{PO}_4)_6(\text{OH})_2 + 2\text{H}^+ + 5\text{H}_2\text{O} \tag{13}$$

As explained above, the partial dissolution of OCP-like layers and ACP conserves Ca$_9$(PO$_4$)$_6$ clusters of ~1 nm size as the primary building unit.[11,16] These clusters can aggregate to form hydroxyapatite as described in the literature.[11,12,14,16,18] This interpretation is supported by the slight progressive shift of the position of the Raman peak from 960 to 962 cm^{-1} and the slight decrease of the fwhm of hydroxyapatite (Figure S14).

4. CONCLUDING REMARKS

Time-resolved Raman measurements reveal that amorphous calcium phosphate (Ca(HPO$_4$)$_{1-x}$(PO$_4$)$_{(2/3)x}$·nH$_2$O) has specific Raman signature comprised between 943 cm^{-1} for

ATCP (Ca$_3$(PO$_4$)$_2$·nH$_2$O, x = 1) and 957 cm^{-1} for ACP (CaHPO$_4$·nH$_2$O, x = 0), as shown in the Figures 1, 3, and S9. This specific Raman signature does not overlap with the strongest Raman peaks of crystalline calcium phosphates phases formed at ambient temperature (OCP at 960−962 cm^{-1}, brushite at 990 cm^{-1}, and hydroxyapatite at 962−963 cm^{-1}) and aqueous species (H$_2$PO$_4^-$ at 880 and 1080 cm^{-1}, HPO$_4^{2-}$ at 992−993 cm^{-1}, and PO$_4^{3-}$ at 939 cm^{-1}). Based on these spectral Raman signatures monitored in real-time and under *in situ* conditions, we demonstrate that the ACP that contains only HPO$_4^{2-}$ in its structure (CaHPO$_4$·nH$_2$O, x = 0) has a short lifetime (<5 min) in solution (experiments 1−2 in Table 1, Figures 1−2). Conversely, the ATCP that contains only PO$_4^{3-}$ in its structure (Ca(PO$_4$)$_{(2/3)}$·nH$_2$O or Ca$_3$(PO$_4$)$_2$·nH$_2$O, x = 1) has a much longer lifetime (>24 h) in solution (experiments 3−4 in Table 1, Figure 5). These results are supported by experiment 5 (Table 1), where the ACP contains initially both PO$_4^{3-}$ and HPO$_4^{2-}$ in its structure with x = 0.4. This phosphate composition in ACP varies with time until x = 0.2 prior to its crystallization into a more stable phase. In this case, an intermediate lifetime of ~35 min is measured (Figure 6). In addition to these fundamental insights, the reaction mechanism steps and kinetics during crystallization of brushite and hydroxyapatite can be determined under specific experimental conditions. For example, brushite (CaHPO$_4$·2H$_2$O) forms when the pH is <9.8; amorphous calcium phosphate (ACP: CaHPO$_4$·nH$_2$O) with short lifetime (<2 min) and octocalcium phosphate (OCP: Ca$_8$(HPO$_4$)$_2$(PO$_4$)$_4$·5H$_2$O) are the main transient phases prior to the nucleation of brushite that occurs after ~8 min (see reactions 3−5). When pH is >11, the hydroxyapatite (Ca$_{10}$(PO$_4$)$_6$(OH)$_2$) nucleates rapidly, after about 35 min, depending on the experimental conditions. Herein, amorphous calcium phosphate with different chemical compositions (ATCP: Ca(HPO$_4$)$_{1-x}$(PO$_4$)$_{(2/3)x}$·nH$_2$O, x from 0.2 to 1) and with different lifetimes can form and then transform into OCP-like layers. Then, the OCP transient phase transforms into hydroxyapatite. The ATCP phase can also transform directly into hydroxyapatite when pH is >12.2, without forming OCP as an intermediate phase (see reactions 6−10 and/or 11−13). In conclusion, the present study reports fundamental insights into the formation of amorphous calcium phosphate phases and their transformation into brushite microcrystals or hydroxyapatite nanocrystals under abiotic conditions, relevant to technological applications and/or natural settings.

The early formation of amorphous phases and their transformation into transient or stable crystalline phases are now considered to be a generalized reaction pathway during the formation of calcium carbonate and phosphate minerals and/or biominerals in aqueous systems. This crystallization pathway agrees with Ostwald's rule, but transient phases are not necessary polymorphs; in fact, they can have different chemical compositions and different particle sizes. Moreover, thermodynamic and kinetic arguments should be considered in the crystallization tendency (e.g., ref 38 and this study). In this way, multisteps nucleation events may exist and combine various reaction mechanisms at the solid−fluid interfaces. Thus, solid-state transition, dissolution−recrystallization, self-assembly aggregation, and partial dissolution−aggregation may operate together during nucleation and growth processes (e.g., refs 31−33 and the present study). In this case, the classical nucleation theory (CNT), the most common theoretical formalism to quantify nucleation and growth rates (including

variation of particles size distribution), cannot successfully be applied in its original formalism as proposed in the last three decades by various research groups (e.g., refs 39−42). These groups have proposed an alternative descriptive approach called nonclassical nucleation and crystallization pathways (including prenucleation clusters). However, in the absence of a theoretical quantitative formalism to describe the so-called nonclassical nucleation, the improved and/or adapted classical nucleation theory remains the best tool to simulate non-classical nucleation of crystals and/or particles (e.g., refs 12, 43−45).

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.jpcc.0c04028.

Table S1 and Figures S1−S14 as described in the text (PDF)

Time evolution of the peaks of the main mineral phases during experiment 1 (AVI)

Time evolution of the peaks of the main mineral phases during experiment 3 (AVI)

Time evolution of the peaks of the main mineral phases during experiment 5 (AVI)

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Notes

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