INTRODUCTION

The past several years have witnessed rapid advances in synthesis and applications of all-inorganic perovskite CsPbX$_3$ (X = Cl, Br, and I) nanocrystals (NCs). In sharp contrast to traditional semiconductor NCs [e.g., CdSe quantum dots (QDs) and InP QDs], the high ionic bonding character renders the formation of CsPbX$_3$ within seconds. More importantly, because of their spectacular array of attractive properties such as high defect tolerance, narrow emission bandwidth, and high photoluminescence quantum yield (PLQY), this class of emerging materials provides new opportunities for use in optoelectronic devices, including solar cells, light-emitting diodes (LEDs), lasers, photodetectors, and so on. Despite significant progress that has been achieved in synthesis of CsPbX$_3$ NCs, it remains a grand challenge toward their practical applications as they suffer from intrinsic chemical instability. First, their ionic character suggests a poor moisture tolerance. CsPbX$_3$ NCs degrade rapidly in the presence of moisture. Second, the weakly bounded surface ligands, typically in the form of an ion pair of carboxylic acid and amine, are easily dissociated from the surface of NCs during purification with antisolvents, thereby resulting in poor moisture tolerance. Third, a fast yet an unavoidable anion exchange occurs when mixing CsPbX$_3$ NCs of different compositions, leading to the composition homogenization. For example, a room-temperature mixing of CsPbBr$_3$ and CsPbI$_3$ NCs yields CsPbBr$_{1.5}$I$_{1.5}$ NCs, and their emission is situated between the respective term. More importantly, because of their spectacular array of attractive properties such as high defect tolerance, 

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emissions of the two constituents. Such color instability disqualifies perovskite NCs for imaging applications where different colors are highly desired to span over the visible spectral range. Fourth, phase instability of CsPbX₃ NCs is also a widely recognized issue. Notably, it has been reported that all CsPbX₃ NCs crystallize in their cubic phase and remain also a widely recognized issue. Notably, it has been reported that all CsPbX₃ NCs crystallize in their cubic phase and remain stable in this phase owing to high synthesis temperature and contributions from surface energy. Particularly, for CsPbI₃ NCs, their perovskite phase (e.g., cubic phase) was found to be metastable under ambient conditions. As a result, they undergo a rapid cubic-to-orthorhombic phase transition, thus diminishing their fluorescent properties. This is not surprising because the orthorhombic phase is thermodynamically stable for a bulk CsPbI₃ material below 315 °C. Finally, for all-inorganic mixed-halide perovskites, for example, CsPbBr₃₋ₓIₓ NCs, they are ubiquitously plagued by phase segregation, leading to the degradation of emission.

Clearly, there is a tremendous need to improve stability of CsPbX₃ NCs for rendering their commercially viable applications. To this end, many efforts have recently been centered on addressing the instability issues noted above, including coating CsPbX₃ NCs with polyhedral oligomeric silsesquioxane, incorporating CsPbX₃ NCs in mesoporous silica, and purifying CsPbI₃ NCs using methyl acetate as an antisolvent to prevent the dissociation of the surface ligand during the purification process.

Herein, we report an effective strategy to achieve CsPbX₃ NCs with greatly improved water, compositional, phase, and phase segregation stabilities by impregnating them within solid organic salt matrices [i.e., metal stearate (MSt)], that is, forming CsPbX₃−MSt nanocomposites. MSt used in our study includes aluminum stearate (AlSt₃), zinc stearate (ZnSt₂), and sodium stearate (NaSt). The introduction of the MSt solid into the CsPbX₃ NC solution leads to the coprecipitation of MSt (NaSt, ZnSt₂, and AlSt₃) and CsPbX₃ NCs. The subsequent centrifugation process readily removes the excessive ligands and precursors without the need of using antisolvents. The resulting CsPbX₃−MSt nanocomposites exhibit excellent optical properties with an impressive set of high stabilities.

RESULTS AND DISCUSSION

A set of CsPbX₃ NCs (X = Br, Br/I, and I) were synthesized (see the Experimental Section). Figure 1a shows the UV−vis and PL spectra of CsPbBr₃ NCs in toluene synthesized at 160 °C, where a band edge at 498 nm and a PL emission peak at 517 nm (i.e., green emission) are observed. These green-
CsPbBr3 is also included as the reference. The emergence of shaped CsPbBr1.5I1.5 NCs is approximately 11.0 nm. The XRD fwhm of 32 nm and PLQY of 67%. The average size of cubic- and their PL emission peak is centered at 612 nm with the toluene solution is orange-emitting under UV irradiation, transmission electron microscopy (HRTEM) of CsPbBr3 nanocomposites. The MSt powder is added into the oleyl- coordination bonding of St and PL emission peak at 664 nm with an fwhm of 39 nm. With more AlSt3 added, an even lighter color can be seen in the supernatant under ambient light and weaker PL was found under 365 nm UV light irradiation. Such progressive decrease of PL intensity of the supernatant (Figure S2c) indicates that less CsPbBr3 NCs are present in the supernatant, signifying that CsPbBr3 NCs are impregnated within the AlSt3 matrix.

Digital images of as-prepared CsPbBr3, CsPbBr1.5I1.5, and CsPbI3 NC toluene solutions and the corresponding CsPbX3 NCs in toluene and the corresponding CsPbX3 nanocomposites in the dry state, respectively. The PL peaks are less CsPbBr3 NCs are present in the supernatant, signifying a slight red-shift compared to as-prepared perovskite NC toluene solutions under UV light excitation. Figure 2c shows the PL spectra of CsPbX3 NCs in toluene and the corresponding CsPbX3−MSt nanocomposites demonstrate similar colors compared to as-prepared perovskite NC toluene solutions under UV light excitation. Figure 2c shows the PL spectra of CsPbX3 NCs in toluene and the corresponding CsPbX3−MSt nanocomposites in the dry state, respectively. The PL peaks are centered at 521 nm for CsPbBr3−AlSt3, CsPbBr1.5I1.5−AlSt3, and CsPbI3−AlSt3 nanocomposites in the dry state, respectively, in their dry states, representing a slight red-shift compared to their NC toluene solution counterparts due likely to a slight aggregation of perovskite NCs when impregnated in AlSt3.

Figure S3 compares transmission electron microscopy (TEM) images of pure AlSt3 and CsPbBr3−AlSt3 nanocomposites. It is clear that pure AlSt3 is irregular, whereas CsPbBr3−AlSt3 nanocomposites contain cubic-shaped CsPbBr3 NCs dispersed in the AlSt3 matrix with a slight aggregation. Figure S4 displays fluorescent micrographs of CsPbBr3−AlSt3, CsPbBr1.5I1.5−AlSt3, and CsPbI3−AlSt3 nanocomposites, emitting cyan, orange, and red fluorescence, respectively.

emitting NCs have a finite full width at half-maximum (fwhm) of 30 nm, indicating a narrow size distribution. The PLQY of CsPbBr3 NCs is 81%. The crystal structure is shown in Figure 1b. The standard X-ray diffraction (XRD) pattern of bulk CsPbBr3 is also included as the reference. The emergence of crystal planes of (100), (110), (200), (211), and (220) suggest the formation of the cubic phase of CsPbBr3 NCs. As-synthesized CsPbBr3 NCs possess the cubic shape with an average size of 10.5 nm (Figure 1c). High-resolution transmission electron microscopy (HRTEM) of CsPbBr3 NCs is shown in Figure 1d. The interplanar distance is measured to be 0.59 nm, which coincides with the (100) plane of CsPbBr3 NCs. For CsPbBr3 NCs, their PL emission peak is centered at 612 nm with the fwhm of 32 nm and PLQY of 67%. The average size of cubic-shaped CsPbBr3 NCs is approximately 11.0 nm. The XRD measurement shows that CsPbBr3 NCs have cubic phase (Figure S1a,c,e). Similarly, CsPbI3 NCs synthesized at 120 °C have the PL emission peak at 664 nm with an fwhm of 39 nm and PLQY of 52%, emitting red fluorescence upon UV excitation. They are cubic shaped as well with an average size of 9.6 nm and have a cubic phase (Figure S1b,d,f).

Figure 2a depicts the stepwise formation of CsPbX3−MSt nanocomposites. The MSt powder is added into the oleylamine (OLA)-capped CsPbX3 NCs toluene solution. The organic salts (MSt) rapidly precipitate together with CsPbX3 NCs from the mixed dispersion solution within several minutes (i.e., coprecipitation of St and CsPbBr3 NCs from the mixed dispersion solution within several minutes (i.e., coprecipitation of CsPbX3 NCs via the coordination bonding of St−Cs and St−Pb (i.e., replacing the original OLA ligands) but also the ionic interaction between metal ions in MSt and X− in CsPbX3 as will be further discussed later, thus leading to the coprecipitation of MSt and CsPbBr3 NCs. Such a behavior is evidenced by weak PL from the supernatant, whereas the precipitates (i.e., CsPbX3−MSt nanocomposites) emit bright fluorescence under 365 nm UV light excitation. After collecting the precipitates by centrifugation, they were dried in an oven to yield the final product. Figure S2 shows that after adding AlSt3 into the CsPbBr3 NC toluene solution followed by centrifugation, the supernatant displays a light color (Figure S2a) and weak PL (Figure S2b).

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respectively, when excited with 365 nm UV light. These micrographs further corroborate that perovskite NCs are distributed within an AlSt₃ solid matrix.

It is notable that in addition to AlSt₃, other stearate salts (NaSt and ZnSt₂) were also investigated. When NaSt was employed to encapsulate CsPbX₃ NCs, a red-shift of PL maximum over pristine CsPbX₃ NCs can be found in resulting CsPbX₃−NaSt nanocomposites (Figure S5). Similarly, such a red-shift is due likely to the aggregation of CsPbX₃ NCs during the coprecipitation process. Interestingly, for ZnSt₂, a PL blue-shift was observed in resulting CsPbX₃−ZnSt₂ nanocomposites (Figure S6), compared to that of the pristine CsPbX₃ NCs. This blue-shift may result from partial cation exchange between Pb²⁺ and Zn²⁺. A similar phenomenon, that is, cation exchange between Pb²⁺ and divalent ions (e.g., Cd²⁺, Zn²⁺, and Sn²⁺), has been reported.³⁹

It is well known that whether an ABX₃ perovskite structure can be formed and sustained is assessable by the Goldschmidt tolerance factor

\[ t = \frac{(r_A + r_X)}{\sqrt{2}(r_B + r_X)} \]

where \( r_A, r_B, \) and \( r_X \) are the ionic radii of the respective ions in ABX₃. An ABX₃ perovskite structure is sustainable if the tolerance factor is between 0.8 and 1.1.¹¹ As summarized in Table S1, the tolerance factor of CsZnBr₃ is 0.933, which is within the tolerance factor range noted above to allow for the formation of a stable perovskite structure. Thus, partial cation exchange may occur between Pb²⁺ and Zn²⁺, leading to a blue-shift of the PL maximum. This can be rationalized as follows. The incorporation of smaller Zn²⁺ results in the contraction of PbBr₆ octahedra, resulting in shorter Pb−Br bonds and thus stronger interactions between Pb and Br orbitals.³⁹ As the conduction band minimum is composed of antibonding combinations between Pb 6p and Br 4p orbitals,⁴² it shifts to higher energy with stronger interaction. As a result, the band gap of perovskite NCs increases and their PL maximum blue-shifts. In contrast, for NaSt, the tolerance factors of NaPbBr₃ and NaPbI₃ are 0.752 and 0.749, respectively, which are smaller than 0.8. Consequently, no cation exchange occurs between Na⁺ and Cs⁺.

Different mass ratios of CsPbBr₃ NCs to stearate salts were investigated to examine their influence on the PL spectra (Figure S7). For NaSt and AlSt₃, the extent of the red-shift in the PL maximum of the resulting nanocomposites decreases as the CsPbBr₃ NC/stearate salt mass ratio decreases. As noted above, the red-shift is induced by the aggregation of perovskite NCs during their impregnation into NaSt and AlSt₃. It is not surprising that a lower mass ratio results in a lower degree of aggregation, as evidenced in Figure S8, which in turn causes a smaller red-shift. For ZnSt₂, as the mass ratio increases, the PL maximum of CsPbBr₃−ZnSt₂ nanocomposites further blue-shifts because more ZnSt₂ is introduced, leading to an increased cation exchange between Pb²⁺ and Zn²⁺.

We also studied the effect of solvents (toluene and hexane) used to disperse perovskite NCs during the NC encapsulation process by MST on their PL (Figure S9). The dispersions of pristine CsPbBr₃ NCs only are also included for comparison. Clearly, CsPbBr₃−NaSt and CsPbBr₃−AlSt₃ nanocomposites display the PL red-shift, regardless of toluene or hexane used. The PL blue-shift can be found for CsPbBr₃−ZnSt₂ nanocomposites in both toluene and hexane when they are used for CsPbBr₃ NCs dispersion. However, the PL blue-shift in toluene is larger than that in hexane. This is because of the different solubilities of ZnSt₂ in toluene and hexane. ZnSt₂ is partially dissolved in toluene, thus the cation exchange reaction between CsPbBr₃ NCs and ZnSt₂ is relatively fast and efficient. In contrast, ZnSt₂ cannot be dissolved in hexane, leading to a slow and inefficient cation exchange of CsPbBr₃ NCs and ZnSt₂.

Figure 3 compares the XRD patterns of CsPbBr₃ NCs, CsPbBr₃−AlSt₃ nanocomposites, and pure AlSt₃ powders. All diffraction peaks of CsPbBr₃ NCs can be readily identified in the XRD spectrum of CsPbBr₃−AlSt₃ nanocomposites, signifying that the crystal structures of CsPbBr₃ NCs are retained in nanocomposites. Specifically, CsPbBr₃−AlSt₃ nanocomposites have the diffraction peaks at 2θ of 15.1°, 21.4°, and 30.4°, corresponding to the (100), (110), and (200) crystalline planes of CsPbBr₃ NCs. The diffraction peaks at 2θ of 6.7°, 11.5°, 19.5°, and 23.2° are from the AlSt₃ matrix. Clearly, these results suggest that the cubic structure of CsPbBr₃ NCs is well preserved after the impregnation of CsPbBr₃ NCs in the AlSt₃ matrix. We note that the peak intensities from CsPbBr₃ are relatively weak compared to those of AlSt₃ as the latter is the matrix.

To investigate the interaction between CsPbBr₃ and AlSt₃ in nanocomposites, Fourier transform infrared (FTIR) and X-ray photoelectron spectroscopy (XPS) studies were performed. Figure 4 depicts the FTIR analysis of CsPbBr₃ NCs and CsPbBr₃−AlSt₃ nanocomposites with different CsPbBr₃/AlSt₃ ratios. For CsPbBr₃ NCs, the stretching vibrations of N−H at 3030 cm⁻¹, C−H at 2925 and 2854 cm⁻¹, C−C at 1608 cm⁻¹, and C−N at 1382 cm⁻¹ as well as the bending vibration of C−H at 908 cm⁻¹ are observed, revealing the presence of surface capping ligands (i.e., OLA). In contrast, FTIR spectra of nanocomposites show the disappearance of N−H, C−C, and C−N vibrations, indicating the absence of OLA. The vibrations of CsPbBr₃−AlSt₃ nanocomposites are at the same wavenumbers as those of AlSt₃, representing the presence of AlSt₃. Moreover, XPS studies of O 1s, C 1s, and N 1s are shown in Figure S10, where both O 1s and C 1s peaks shift to larger binding energies after the impregnation of CsPbBr₃ NCs in AlSt₃. N 1s peaks can be clearly observed in CsPbBr₃ NCs, whereas they cannot be detected in CsPbBr₃−AlSt₃ nanocomposites, suggesting the absence of OLA in CsPbBr₃−AlSt₃ nanocomposites. These results suggest that during the coprecipitation process, the original OLA ligands on the
surface of CsPbBr₃ NCs were exchanged by AlSt₃ as discussed in the mechanism above.

XPS studies revealed that after encapsulation by AlSt₃, all Cs 3d, Pb 4f, and Br 3d peaks are shifted to larger binding energies, particularly Pb 4f and Br 4d peaks (Figure 5). This may suggest the coordination bond of St−Cs and St−Pb and the ionic bond between metal ions from MSt and X− on the surface of CsPbX₃. On the basis of XPS and FTIR measurements, we propose a plausible mechanism of AlSt₃ encapsulation for yielding CsPbBr₃−AlSt₃ nanocomposites. In the presence of AlSt₃, the weakly bound surface ligands OLA are exchanged by AlSt₃. As a result, Al³⁺ preferentially adsorbs to the surface of NCs via Al³⁺−Br⁻ interaction, accompanied by a long St chain situating on the surface of NCs or coordinating with Cs⁺ and Pb²⁺ of NCs. Such a straight St chain promotes van der Waals attraction between adjacent NCs through the interdigitation of St chains from adjacent NCs and accordingly imparts the aggregation of NCs. Similar ligand-dependent colloidal stability has been reported in CdSe QDs. For the saturated solution of CdSe QDs, a dramatically decreased solubility was observed as the length of n-alkanoate ligands change from C₁₄ to C₂₂, which was ascribed to the increased van der Waals attraction of QDs via the ligand interdigitation between neighboring QDs.

The PL lifetime of CsPbBr₃ NCs and CsPbBr₃−AlSt₃ nanocomposites was studied (Figure S11 and Table S2). It is clear that CsPbBr₃−AlSt₃ nanocomposites possess a longer lifetime than that of CsPbBr₃ NCs, which can be ascribed to the surface passivation of AlSt₃.

In the work that follows, we demonstrate an impressive set of excellent stabilities that CsPbX₃−MSt nanocomposites carry, including water stability, compositional stability, phase stability, and phase segregation stability. First, we take CsPbBr₃−AlSt₃ nanocomposites as an example to showcase high water resistance of CsPbBr₃−AlSt₃ nanocomposites (Figure 6b). Sonication was applied to assist in the homogenous mixing between liquid/liquid (water/toluene) and liquid/solid (water/nanocomposites) phases. For CsPbBr₃ NCs in toluene, after addition of water followed by sonication, the solution emission becomes weaker and completely disappears after 25 min (Figure 6a). In stark contrast, after sonication for 25 min, CsPbBr₃−AlSt₃ nanocomposites still display bright PL and remain highly luminescent even after being stored overnight.

The compositional stability (i.e., anion exchange stability) of CsPbX₃−MSt nanocomposites was then evaluated. As shown in Figure 7a, immediately after mixing CsPbBr₃ and CsPbI₃ NC powders together, the two PL peaks merge into a broadened peak (mixture 1) with much reduced intensity composed of several subpeaks situated between the original CsPbBr₃ and CsPbI₃ PL emissions because of the partial anion exchange between Br⁻ and I⁻. After 1 h, these broad PL peaks merge into a narrow single peak (mixture 2 in Figure 7a), signifying the complete anion exchange. Taking the mixing of CsPbBr₃−AlSt₃ and CsPbI₃−AlSt₃ nanocomposites as an example, it is notable that there was no salient PL peak position and intensity change even after mixing these two
nanocomposites for one day. Clearly, these results corroborate that CsPbBr$_3$ and CsPbI$_3$ NCs encapsulated within the respective AlSt$_3$ matrix are well protected and effectively isolated from each other preventing them from anion exchange.

As for phase stability of nanocomposites, CsPbI$_3$−AlSt$_3$ was used as an example. We first investigated their PL under ambient conditions. For comparison, the PL of CsPbI$_3$ NCs was also measured. Figure 8a shows that the PL intensity of CsPbI$_3$ NCs in toluene drops quickly within 10 days. The XRD measurements clearly suggest the phase transition of CsPbI$_3$ NCs. The freshly synthesized CsPbI$_3$ NCs have a cubic phase and transform into an orthorhombic phase after 10 days. Figure S12 illustrates the schematic of cubic and orthorhombic structures. In sharp contrast, the CsPbI$_3$−AlSt$_3$ nanocomposites still maintain 85% of the original PL intensity after 30 days (Figure 8b). Moreover, no orthorhombic phase can be found in the XRD pattern of nanocomposites after 30 days (Figure 8d), which is comparable to those reported in the literature (Table S3). These results demonstrate that the passivation of CsPbI$_3$ NCs with AlSt$_3$ is highly effective and greatly suppresses the phase transformation of CsPbI$_3$ NCs from the emissive cubic phase to nonemissive orthorhombic phase. There are two reasons which may account for the phase stability of CsPbI$_3$ NCs after impregnation in AlSt$_3$. First, AlSt$_3$ can effectively isolate CsPbI$_3$ NCs from the surrounding environment containing moisture and oxygen that accelerate the phase transition of CsPbI$_3$ NCs from cubic to orthorhombic. Second, AlSt$_3$ may release the lattice strain which is the driving force for phase transition of CsPbI$_3$ NCs. Notably, it has been reported that the lattice strain causes the intrinsic instability of the cubic phase at ambient temperature and drives the phase transformation into the orthorhombic phase.27,35 Similar phase stability was also found in CsPbI$_3$−NaSt and CsPbI$_3$−ZnSt$_2$ nanocomposites. As shown in Figure S13, both CsPbI$_3$−NaSt and CsPbI$_3$−ZnSt$_2$ nanocomposites display high PL intensity after 30 days.

Notably, as-prepared nanocomposites also possess remarkable phase segregation stability. In this regard, CsPbBr$_{1.5}$I$_{1.5}$ NCs and CsPbBr$_{1.5}$I$_{1.5}$−AlSt$_3$ nanocomposites were examined and compared, revealing that AlSt$_3$ impregnation can effectively prevent phase segregation and retain their structural stability. Figure 9a depicts that within 20 days, the PL intensity of CsPbBr$_{1.5}$I$_{1.5}$ NCs drops quickly and the PL maximum blue-shifts largely, which is consistent with the previous report in the literature.44 By contrast, after AlSt$_3$ encapsulation, there is only a slight decrease in PL intensity of CsPbBr$_{1.5}$I$_{1.5}$−AlSt$_3$ NCs drops quickly and the PL maximum blue-shifts largely, which is consistent with the previous report in the literature.44 By contrast, after AlSt$_3$ encapsulation, there is only a slight decrease in PL intensity of CsPbBr$_{1.5}$I$_{1.5}$−AlSt$_3$ nanocomposites. No detectable PL peak shift can be observed, suggesting no phase segregation (i.e., forming the respective CsPbBr$_3$ and CsPbI$_3$; Figure 9b). This is also due probably to the AlSt$_3$ encapsulation offsets lattice strain which improves the phase stability. These results clearly indicate that the AlSt$_3$ encapsulation is robust and prevents the phase segregation of mixed-halide perovskite.

As described above, CsPbX$_3$−MSt nanocomposites exhibit a suite of excellent stabilities. Subsequently, WLED composed of
CsPbX₃–MSt nanocomposites was assembled, manifesting the appealing performance, including a high color rendering index ($R_a$) and a low color temperature ($T_c$). Commercially available WLEDs usually involve the use of a blue-emitting InGaN chip as the excitation source and Y₃Al₅O₁₂:Ce³⁺ (YAG:Ce³⁺) yellow phosphors as the color conversion layer. However, such WLEDs suffer from low $R_a$ (<80) as YAG:Ce³⁺ phosphors have limited red spectrum emission. In an attempt to solve this problem, a WLED was crafted by employing the mixture of YAG:Ce³⁺ phosphors, CsPbBr₁.₅I₁.₅ NCs, and epoxy deposited on a blue InGaN chip.Figure 10 shows the electroluminescence (EL) spectrum of the constructed WLED when electrically driven. Bright and warm white light is emitted with a high $R_a$ of 89.9, a low $T_c$ of 4588 K, a CIE color coordinate of (0.35, 0.33), and an efficacy of 56.54 lm/w under 30 mA driven current. For comparison, a WLED by employing the mixture of YAG:Ce³⁺ phosphors, CsPbBr₁.₅I₁.₅ NCs, and epoxy deposited on a blue InGaN chip was also fabricated (Figure S14), yielding a much lower efficacy. These results signify the great potential of CsPbX₃–MSt nanocomposites for use as solid-state luminophores in WLEDs and other practical optoelectronic applications.

**CONCLUSIONS**

In summary, we have developed a simple yet robust strategy to craft a new class of CsPbX₃–MSt nanocomposites (where $X =$
impregnated within the AlSt3 matrix sustain high emission for at least one month, that is, a demonstration of water stability. Moreover, when mixing CsPbBr3−AlSt3 and CsPbI3−AlSt3 nanocomposites together, an anion exchange between them (i.e., Br− and I− exchange) is virtually arrested because of the efficient coating and separation of the respective CsPbX3 by AlSt3, that is, a manifestation of compositional stability. Furthermore, for CsPbI3 NCs, the cubic phase is metastable at room temperature and readily transformed into the PL-inactive orthorhombic phase. After coating with AlSt3, the resulting CsPbI3−AlSt3 nanocomposites preserve the cubic phase of CsPbI3 and high emission for at least one month, that is, a demonstration of phase stability. Finally, CsPbBr3−AlSt3 NCs impregnated within the AlSt3 matrix sustain high emission without degradation for at least one month, that is, a display of phase segregation stability. These optically active, highly stable nanocomposites on a blue InGaN chip. Inset: WLED operated under 30 mA driven current.

**EXPERIMENTAL SECTION**

Materials. Oleic acid (OA, 90%), OLA (90%), 1-octadecene (ODE, ≥90%), toluene, hexane, sodium stearate (NaSt, ≥98%), zinc stearate (ZnSt2, 99%), aluminum stearate (AlSt3, ≥99%), and transparent epoxy JH-6800MA and JH-6800MB were purchased from APT Electronics Ltd. Lead bromide (PbBr2, 98%), lead iodide (PbI2, 99%), toluene, hexane, sodium stearate (NaSt, ≥98%), zinc stearate (ZnSt2, 99%), aluminum stearate (AlSt3, ≥99%), and transparent epoxy JH-6800MA and JH-6800MB were purchased from Sinopharm Chemical Reagents Co. Ltd. Lead bromide (PbBr2, 98%), lead iodide (PbI2, 99%), and cesium carbonate (Cs2CO3, ≥98%) were from Aladdin. All of the raw materials were used directly without further purification. Blue InGaN LED chips (450 nm) with a power of 0.1 W were purchased from APT Electronics Ltd.

Preparation of Cs-Oleate. Cs-oleate was prepared by following a previously reported procedure.7 Cs2CO3 (0.8 g), OA (2.5 mL), and ODE (30 mL) were added into a 100 mL three-neck flask and degassed for 1 h at 120 °C, and then heated to 150 °C under N2 flow until the solution turned clear. We note that the Cs-oleate ODE solution has to be preheated to 100 °C prior to injection to the PbX3 ODE solution as Cs-oleate precipitates out of ODE at room temperature.

**Synthesis of CsPbX3 NCs.** ODE (5 mL) and PbX2 [0.188 mmol; i.e., PbI2 (0.087 g), PbBr2 (0.069 g), or a mixture of PbI2 (0.0435 g) and PbBr2 (0.0345 g)] were added into a 25 mL three-necked flask and degassed for 1 h at 120 °C. Dried OLA (0.5 mL) and OA (0.5 mL) were injected into the PbX2 ODE solution at 120 °C under N2. After the solution turned clear, the temperature was raised to 120–160 °C, and the Cs-oleate solution (0.4 mL) was quickly introduced, and 5 s later, the reaction mixture was cooled by an ice-water bath.

**Impregnation of CsPbX3 NCs within MSt Salts.** A crude solution of as-synthesized CsPbX3 NCs was dissolved in toluene and centrifuged at 6500 rpm for 10 min. The supernatant was discarded, and the precipitation was redispersed in toluene and centrifuged at 6500 rpm for 10 min. Then, the precipitate was dispersed and 50 mg MSt was added to the supernatant (25 mg/mL) under vigorous stirring. The MSt used in this work includes aluminum stearate (AlSt3), zinc stearate (ZnSt2), and sodium stearate (NaSt). After 10 min, the stirring was stopped, and the mixed solution was allowed to precipitate. After centrifugation at 5000 rpm for 5 min, the supernatant was discarded, whereas the precipitate was dried in an oven at 60 °C overnight.

**Fabrication of WLED.** Typically, epoxy resin was used as the encapsulating material in the packaging of LEDs. Equal amounts of transparent epoxy (JH-6800MA and JH-6800MB) were mixed together, after which cerium-doped yttrium aluminum garnet (YAG:Ce4+) phosphors and as-prepared CsPbBr3−AlSt3 NCs−AlSt3 nanocomposites were added. The mixture was stirred thoroughly and then dispersed on the InGaN LED chip. The coated WLED chip was solidified in an oven at 80 °C for 2 h.

**Characterization.** All measurements were performed at room temperature. Ultraviolet-visible (UV–vis) absorbance spectra of the CsPbX3 NCs toluene solution were obtained using a Shimadzu UV-2550 UV–vis spectrophotometer. PL spectra of the CsPbX3 NCs toluene solution and CsPbX3−MSt nanocomposites were recorded using a HitachiF-4600 fluorescence spectrophotometer. TEM and HRTEM images of CsPbBr3 NCs, as well as TEM images of CsPbBr3−AlSt3 nanocomposites were obtained by a JEM-2100 field emission source TEM. Optical micrographs of CsPbX3−AlSt3 nanocomposites were taken using an Olympus SZX16 fluorescence microscope. XRD studies were performed using a RigakuD/MaxB X-ray diffractometer to identify the crystalline phases and structures of CsPbX3 NCs and CsPbX3−AlSt3 nanocomposites. FTIR spectra of CsPbX3 NCs, AlSt3, and CsPbX3−AlSt3 nanocomposites were acquired by a Nicolet 6700 FTIR spectrometer. XPS studies on...
CsPbBr₃ NCs and CsPbBr₃−AlST₃ nanocomposites were conducted using a Thermo Escalab-250 X-ray photoelectron spectrometer. PL lifetime measurements of CsPbX₃ NCs and CsPbX₃−AlST₃ nanocomposites were performed using an Edinburgh FL 900 photomultiplier with a time-correlated single-photon counting system. Optical properties of the WLED were obtained using an integrating sphere (Everal Photo-E-Info Co., Ltd).

**ASSOCIATED CONTENT**

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acsami.8b13553.

Experimental details and additional figures (PDF)

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Notes

The authors declare no competing financial interest.

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