

Boosting Tunable Blue Luminescence of Halide Perovskite Nanoplatelets through Postsynthetic Surface Trap Repair

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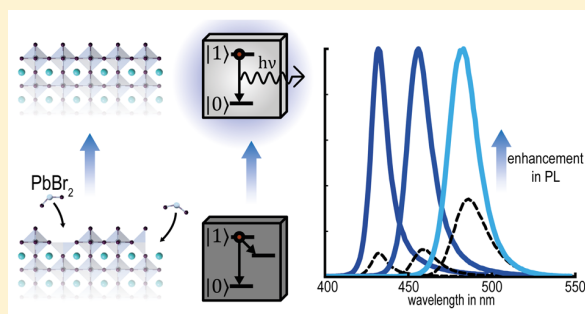
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Supporting Information

ABSTRACT: The easily tunable emission of halide perovskite nanocrystals throughout the visible spectrum makes them an extremely promising material for light-emitting applications. Whereas high quantum yields and long-term colloidal stability have already been achieved for nanocrystals emitting in the red and green spectral range, the blue region currently lags behind with low quantum yields, broad emission profiles, and insufficient colloidal stability. In this work, we present a facile synthetic approach for obtaining two-dimensional CsPbBr₃ nanoplatelets with monolayer-precise control over their thickness, resulting in sharp photoluminescence and electroluminescence peaks with a tunable emission wavelength between 432 and 497 nm due to quantum confinement. Subsequent addition of a PbBr₂-ligand solution repairs surface defects likely stemming from bromide and lead vacancies in a subensemble of weakly emissive nanoplatelets. The overall photoluminescence quantum yield of the blue-emissive colloidal dispersions is consequently enhanced up to a value of 73 ± 2%. Transient optical spectroscopy measurements focusing on the excitonic resonances further confirm the proposed repair process. Additionally, the high stability of these nanoplatelets in films and to prolonged ultraviolet light exposure is shown.

KEYWORDS: CsPbBr₃, perovskite nanocrystals, nanoplatelets, quantum confinement, exciton binding energy, defect passivation, blue light emitting diodes



Halide perovskites in the form of bulk thin films have attracted significant interest owing to rapid rises in photovoltaic efficiencies.^{1–5} Nanocrystals (NCs) of the same material have been garnering strong interest since 2014 for light emission applications due to high photoluminescence quantum yields (PLQYs) approaching unity and an emission wavelength that is tunable throughout the visible range by changing the halide ion.^{6–14} Two of the important limitations currently hindering the widespread use of this material are (i) a very low efficiency of chloride-containing perovskite NCs, and thus only poor performance in the blue spectral range, and (ii) a tendency of mixed-halide perovskite to phase segregate into domains with different halide ion contents and resulting bandgaps, consequently shifting the emission wavelength strongly during operation of LEDs.^{15–20} While most of these NCs are either bulklike or only weakly confined, several studies have shown strong quantum confinement in perovskite NCs as

a further viable method to tune the emission wavelength especially toward the blue spectral range.^{21–23} In particular, two-dimensional (2D) nanoplatelets (NPLs) have been demonstrated with an atomic-precision control over their thickness down to a single monolayer (ML) and large exciton binding energies, an appealing characteristic for light-emitting applications.^{15,24–30} These NPLs are unfortunately strongly susceptible to surface defects due to a large surface-to-volume ratio, rendering their QYs typically quite low.^{18,23,25,26,31} It was often observed that the PLQY of both hybrid and inorganic perovskite NCs drastically decreases with the change in morphology from cubic to platelet form.^{23,24,26,32} For instance,

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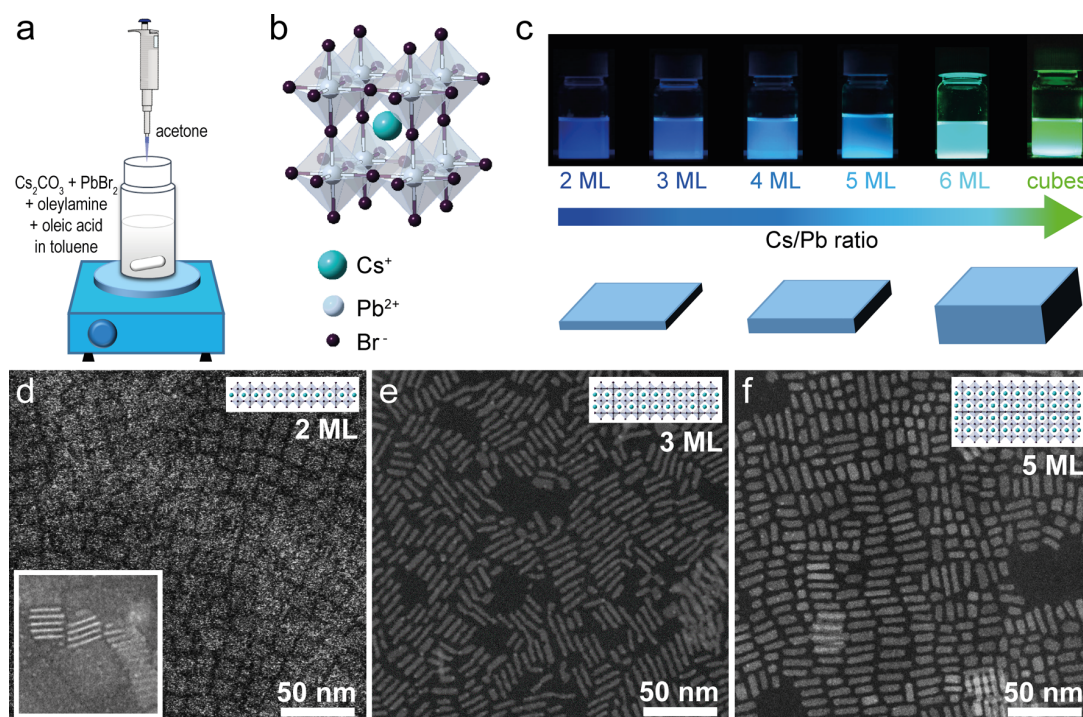


Figure 1. (a) Schematic illustration showing the synthesis of CsPbBr₃ NPLs by reprecipitation of precursors using acetone. (b) Cubic crystal structure of CsPbBr₃ perovskite NCs. (c) Photographs of vials containing the colloidal NPL dispersions (obtained with increasing Cs/Pb ratio) illuminated with UV-light. A steady redshift with increasing ML thickness can be observed. (d–f) ADF-STEM images of 2, 3, and 5 ML NPLs. Inset in (d): stacked 2 ML NPLs standing on their edges.

the PLQY of CsPbBr₃ NCs drops from 78% to 31% with a change of morphology from cubic to thick NPLs.^{23,24} Additionally, it is difficult to produce NPLs of only a single thickness using current synthesis routes, and the resulting NPLs tend to have problems with long-term stability.^{18,26,33–35}

In this work, we present a simple room-temperature synthesis method for obtaining blue-emitting colloidal CsPbBr₃ NPLs with precisely controllable thickness from 2 to 6 MLs. All NPLs exhibit clear excitonic peaks in absorption spectra, which are a result of the increased exciton binding energies in these confined nanostructures, as well as narrow photoluminescence (PL) and electroluminescence (EL) emission. We show that the PLQYs of these NPLs can be significantly enhanced through a postsynthetic treatment by the addition of a PbBr₂-ligand solution. The PLQYs of these NPLs reach up to $73 \pm 2\%$ with the emission color retained, making this NPL series one of the most efficient perovskite blue light-emitters reported to date.³⁶ Differential transmission spectroscopy (DTS) and time-resolved (TR)-PL studies reveal that the enhancement affects a subensemble of the NPLs for which surface defects, initially hindering radiative recombination, are repaired, enhancing the overall emission of the NPL dispersions. Additionally, we show the enhanced stability of the NPLs even under prolonged UV exposure.

The synthesis of CsPbBr₃ NPLs applies the concept of reprecipitation³⁷ with thickness control achieved by regulating the molar ratio of the precursors, as in our previous studies (see Figure 1a–c).^{11,24} Briefly, a Cs-oleate precursor with a specific Cs/Pb ratio for each NPL thickness (cf. Supporting Information Table S1) was added under vigorous stirring into a toluene solution containing a PbBr₂-oleylamine/oleic acid precursor at room temperature (Figure 1a). After 5 s, a large

amount of acetone was added to initiate formation of the NPLs. The reaction was then run for 1 min under continuous stirring, after which the mixture was centrifuged for 3 min and then redispersed in 2 mL of hexane. The thickness of the NPLs was controlled by varying the ratio of the Cs/Pb precursors and the amount of acetone added. The details of the synthesis are given in the Supporting Information (Materials and Methods). The resulting dispersions show a strong difference in color, especially under UV-light, with a clear shift from blue to green with increasing Cs/Pb ratio (see Figure 1c). This is indicative of quantum confinement effects and very similar to our previous findings on hybrid organic–inorganic perovskites, where the MA/Pb ratio was controlled.²⁴ In these two approaches, the amount of the A-site cation (here Cs⁺; previously MA⁺) is decreased with respect to the other precursors, limiting the amount of perovskite that can be formed and the resulting NCs shrink in size or more specifically in thickness. Thus, NPLs with thicknesses down to a single monolayer can be formed. However, one drawback of our previous approach was that the syntheses tended to form NPL dispersions of mixed thicknesses leading to broad PL emission. To investigate the monodispersity of the NCs in our new findings, we employed annular dark-field scanning transmission electron microscopy (ADF-STEM) as shown in Figure 1d–f. For the lowest Cs/Pb ratio, we find regularly sized, low contrast square-shaped NCs with side lengths of 14 ± 4 nm (Figure 1d). The low-contrast signifies very thin NPLs, which is confirmed by images of NPLs standing on their side (see inset), from which we measured a thickness of 1.2 ± 0.1 nm. One ML in this case signifies a 2D arrangement of corner-sharing [PbBr₆]⁴⁻ octahedra with a thickness of 0.59 nm (Figure 1b).^{11,12} Therefore, the measured thickness likely

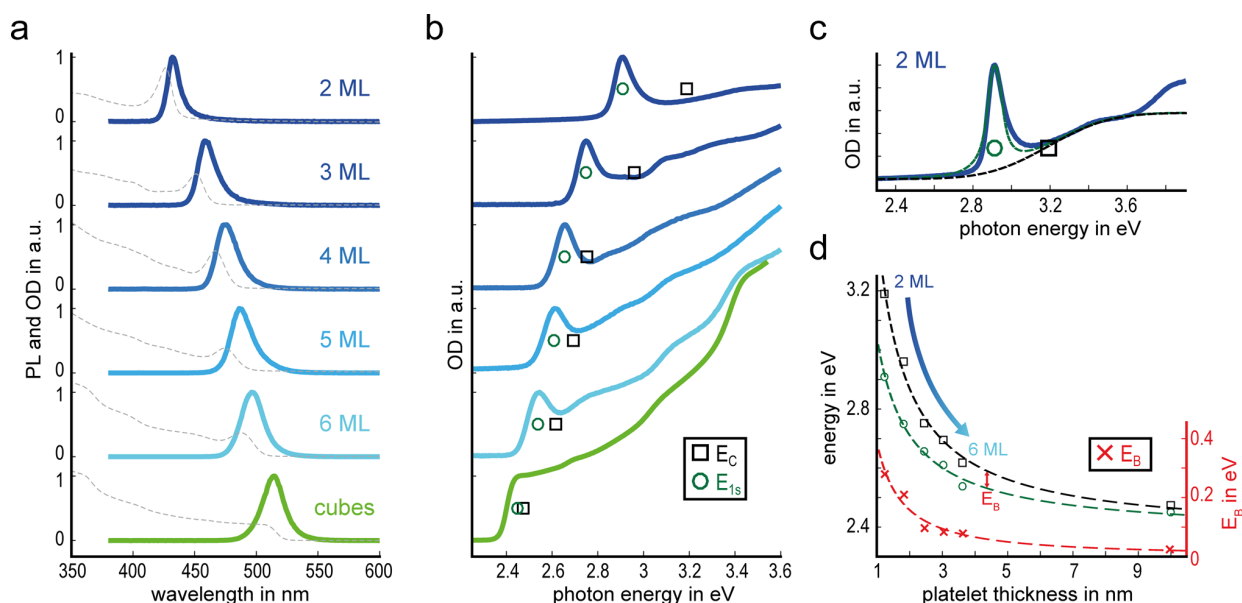


Figure 2. (a) PL (solid lines) and absorption (dashed lines) spectra of NPI colloids for varying NPI thickness. Spectra of weakly confined nanocubes are also shown for comparison. (b) Absorption spectra normalized to the excitonic peak. Green circles indicate the energetic position of the exciton transition E_{1s} and black squares show the corresponding continuum absorption onset E_C for each sample. (c) Model (green dashed line) applied to extract these positions from the experimental data (solid curve, in this case 2 ML) using the excitonic peak and the absorption onset of the continuum (black dashed line). (d) The obtained values for E_C and E_{1s} versus the NPI thickness. Their difference is the exciton binding energy E_B (red crosses), which increases strongly with decreasing NPI thickness. Dashed lines are added as guides to the eye.

corresponds to NPIs comprising two MLs. As the Cs/Pb ratio increases, the thickness of the NPIs also increases (2.0 ± 0.3 and 2.9 ± 0.3 nm for the 3 and 5 ML NPIs, respectively). See Figure 1d–f and also Figure S1 for a detailed analysis of the thickness). Additionally, we find that the lateral size is nearly constant for all of the NPI samples (cf. Figures S1, S2). ADF-STEM imaging and corresponding fast Fourier transform (FFT) patterns confirm the high level of crystallinity of the NPIs, which exhibit an orthorhombic or cubic crystal structure (cf. Figure S5). Additionally, inferred from the higher optical contrast, we observe a strong tendency of the NPIs to arrange in stacks along the substrates, signifying a high uniformity in the lateral size of the NPIs.³⁸ This stacking does not happen in the dispersions, as derived from the lack of any precipitate forming and nearly no scattering observed in the UV–vis spectra. From these analyses, it seems as if the dispersions contain NPIs each with only one specific thickness ranging from 2–6 MLs. This is further confirmed by X-ray diffraction (XRD) analysis. Additionally to the bulk CsPbBr₃ 001 peaks, which signify a high degree of orientation of the NPIs, peaks resulting from stacking of the NPIs are observed (cf. Figure S7). Using these, we obtain spacing values between individual NPIs, which correspond well to the expected thickness of the inorganic layer including a ligand length of 1.5 nm surrounding the NPIs.

In order to confirm this, we turned to optical spectroscopy, probing the linear PL and absorption spectra of each NPI dispersion (Figure 2a,b). Each PL spectrum clearly comprises only a single narrow peak (full width at half-maximum (fwhm) down to 11 nm), with the central peak position blueshifting from 515 to 432 nm with decreasing Cs/Pb ratio in the precursor (Figure 2a). The Cs/Pb ratio used to obtain the 515 nm emission wavelength is comparable to that which we used previously to obtain weakly quantum-confined nanocubes.^{11,39}

The absorption spectra of all NPI samples show a clear absorption onset, with small Stokes shifts of 6–10 nm (Figure 2a). Additionally, as the Cs/Pb ratio is reduced, a clear excitonic absorption peak can be observed and for the lowest ratios, additionally a step-like increase resembling the continuum onset of a 2D semiconductor (Figure 2b). With the spectra being acquired at room temperature, the emergence of the excitonic resonance signifies that the exciton binding energy E_B increases with decreasing Cs/Pb ratio, to an extent that the thermal energy at room temperature is progressively less able to dissociate excitons. As it can be seen in Figure 2b, additional peaks emerge at higher energies, however, these stem from transitions between higher energetic bands and are not considered further.⁴⁰ Similar widths of excitonic absorption peaks and PL emission spectra, small Stokes shifts and the lack of additional peaks in the PL spectra all support the hypothesis that the dispersions actually comprise NPIs of only a single thickness. Accordingly, we confirm the correlation of the observed PL peaks and corresponding dispersions to NPIs with a ML thickness of $n = 2$ up to $n = 6$.¹²

The observed blueshift in the PL spectrum with decreasing Cs/Pb ratio stems from quantum-confinement in the NPIs. This effect generally results in the increase of the continuum absorption onset E_C given by the respective band gap energy of the bulk crystal and the confinement energies of the electron and hole, $E_C = E_G + E_e + E_h$. The exciton binding energy E_B increases simultaneously. As these effects actually shift the resulting PL emission in opposite directions, the shift of E_C must be larger than the increase of E_B in order to induce the observed blueshift. To confirm this, we have modeled the absorption spectra using Elliot's model (Figure 2c). Using a method similar to that suggested by Naeem et al. for 2D platelets,⁴¹ we can assign the continuum absorption onset

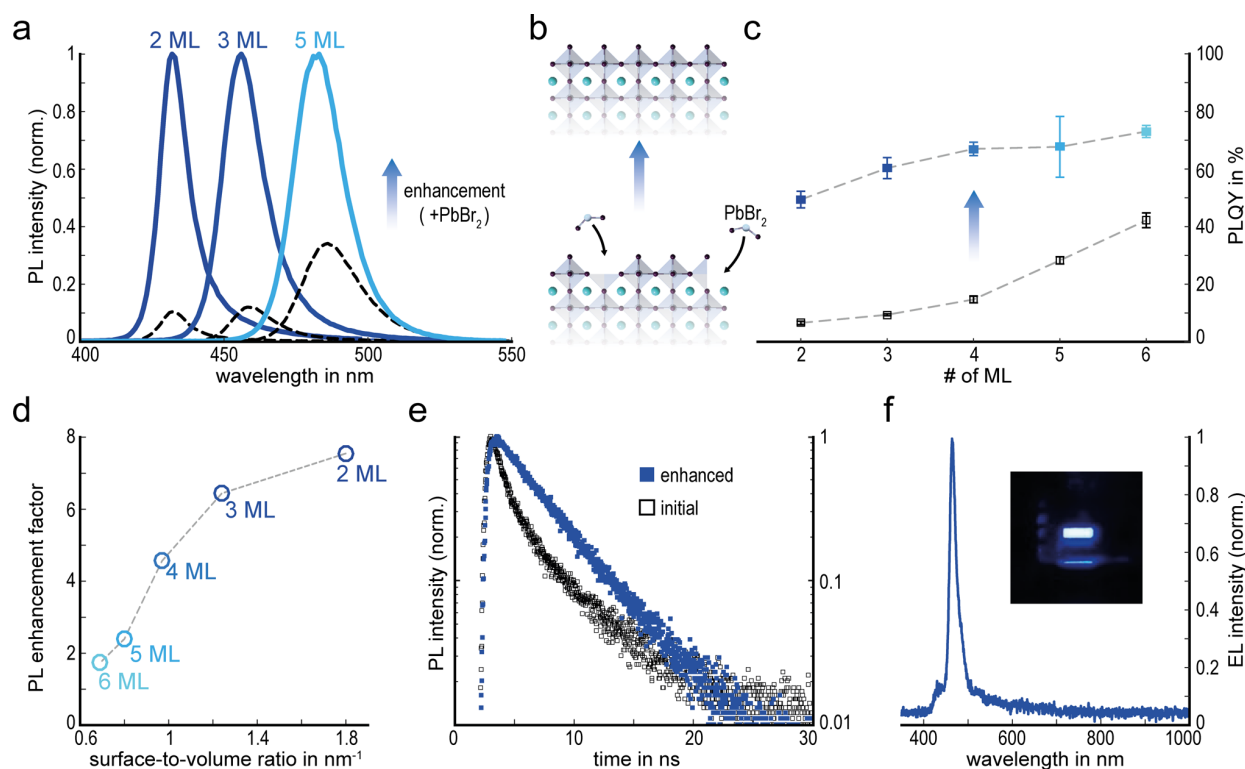


Figure 3. (a) PL spectra of initial NPI colloidal dispersions (black dashed lines) and enhanced dispersions (normalized, solid lines). (b) Scheme for the repair process of surface defects initiated by a chemical post-treatment with a PbBr_2 solution. (c) PLQYs of the NPI dispersions pre-enhancement (open black squares) and postenhancement (full blue squares). $n \geq 6$ values have been averaged for each data point. Dotted lines are guides to the eye. (d) PL enhancement factor as a function of the surface-to-volume ratio. (e) TR-PL of a 3 ML NPI dispersion before (open black squares) and after enhancement (full blue squares). (f) Electroluminescence (EL) spectrum of a light-emitting diode (LED) based on the enhanced 3 ML NPIs. Inset: photo of the working LED.

energy E_C (black squares) and also the energetic position of the dominant $1s$ excitonic transition E_{1s} (green circles) to each of the samples in Figure 2b by modeling the contribution of the excitonic peak and the lowest band of the continuum transitions. These values are important, as their difference is exactly the exciton binding energy: $E_B = E_C - E_{1s}$. This model can be applied through a simple modification to 2D and 3D semiconductors, which apply for the 2 ML and the cube case, respectively. For all other NPIs, the actual structure is somewhere in between, as they are only “quasi-2D” due to their finite thicknesses. Yet, they are also not three-dimensional due to a significant degree of quantum confinement in one direction. We were able to extract values for all NPI thicknesses, which we have plotted in Figure 2d. Clearly, both energies decrease with increasing NPI thickness. The exciton binding energy E_B , being the difference between the two curves, can be seen to increase as the NPI thickness is reduced, reaching a value of 280 meV for the 2 ML case. This is nearly 10 times the value for the cubes of only 30 meV, which corresponds well to previously described values.^{42–45} This strong change can be understood when comparing the excitonic Bohr radius of bulk CsPbBr_3 , reported to be approximately $a_B = 7$ nm with the NPI thickness. Clearly, the 2–6 ML NPIs are far thinner than this, thus they are in the limit of strong quantum-confinement, whereas the cubes with a side length of about 10–12 nm are only in the weak limit.²² Previously, it has been shown that the extraction of E_B by analysis of absorption data is prone to fitting ambiguities in the

case of bulk perovskite crystals⁴⁶ and other approaches have been applied to extract this value.^{42,47} However, here in the case of strong confinement for the NPI dispersions with clearly separated excitonic and continuum absorption, the fitting of absorption data is significantly more reliable.

Whereas the synthesis yields perovskite NPIs with uniform thickness and narrow PL emission spectra, the intensity, especially for the thinnest NPIs, tends to be quite low. In fact, for the 2 and 3 ML samples we determine their PLQY to be only around $7 \pm 1\%$ and $9 \pm 1\%$, respectively. Such low values have commonly been observed and are likely a result of the existence of surface trap states and the high surface-to-volume ratio of these 2D nanostructures.^{23,25} To address this issue, we have developed a postsynthetic treatment of the colloidal NPIs obtained from the previously described synthesis in order to passivate the trap states on the NPI surface.

We discovered that by adding a PbBr_2 -ligand (oleic acid and oleylamine) hexane solution to the NPI dispersion, we can dramatically enhance their PLQYs. Immediately after addition, the PL of the samples is strongly increased, so that the dispersions appear deeply blue even under ambient lighting (see Figure S9). It turns out that the PL intensity of each NPI dispersion can be significantly enhanced, as shown in Figure 3a. The PL peak maxima and absorption features were nearly constant with some samples showing only minor blueshifts (10–15 meV) after the enhancement. This could be due to an increasing of the dielectric constant of the enhanced samples and a blueshift of the excitonic resonance position due to the

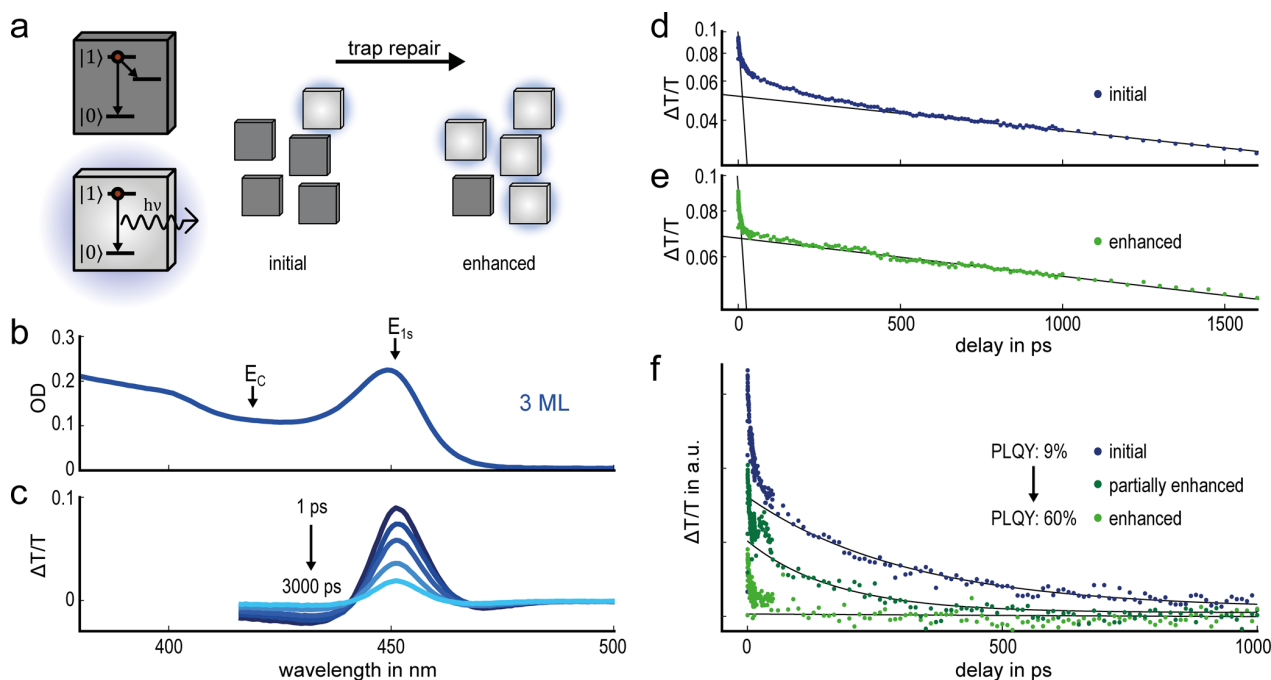


Figure 4. (a) Scheme depicting the postsynthetic trap repair and concomitant increase of the number of defect-free NPLs that exhibit predominantly radiative recombination. (b) Steady-state absorption spectrum and (c) differential transmission spectra at delay times ranging from 1 to 3000 ps after excitation for the 3 ML sample. (d) Transients of differential transmission at the energetic position of the exciton, as shown in (b) (d) an initial and (e) an enhanced 3 ML sample. (f) Transients after subtracting the late time decay corresponding to excitonic recombination. The initial samples show exciton trapping in nonemissive NPLs with surface defects as an additional process, which is slower than exciton–exciton annihilation, but faster than excitonic recombination.

increased Coulomb screening. These results indicate that the treatment enhances the PL efficiency of the colloidal NPLs without affecting their thickness or uniformity, as confirmed through ADF-STEM imaging and XRD measurements (cf. Figures S3 and S8). Furthermore, electron diffraction measurements show that the crystallinity of the NPLs is significantly increased in the enhanced samples (see Figures S4 and S5). Energy-dispersive X-ray (EDX) spectroscopy additionally shows that the ratio of Br/Pb and Pb/Cs ions in the NPLs increases as a result of the enhancement (see Supporting Information for details, Figure S6). To investigate the mechanism, for comparison, we added a similar solution without the PbBr_2 (only the organic ligands in hexane) to the NPL dispersions. As in our previous work, we find that the dilution and additional ligands tend to decompose the NPLs, in this case mainly into their original precursors, as determined through PL spectroscopy (see Figure S10). Furthermore, we applied various additional bromide-salt-ligand solutions (SnBr_2 , KBr , NaBr) in the enhancement step. All of these lead to an enhancement of the PL, albeit of smaller magnitude than for the PbBr_2 -solution (see Figure S11). These results together imply that Br and Pb vacancies at the surface of the NCs are filled by the enhancement solution, with the ligands serving to passivate any uncoordinated surface atoms (see Figure 3b).

The enhancement is effective for all thicknesses from 2 to 6 ML with PLQY values of $7 \pm 1\%$ and $42 \pm 3\%$ for the 2 and 6 ML samples before and $49 \pm 3\%$ and $73 \pm 2\%$ after the enhancement process (Figure 3c). The PLQY values of $49 \pm 3\%$ (2 ML) and $60 \pm 4\%$ (3 ML) are one of the highest reported PLQYs of any perovskite material for an emission

wavelength shorter than 470 nm. Interestingly, we observe that the degree of enhancement is strongly dependent on the thickness of the sample with the PLQYs improving by a much larger factor for the thinnest NPLs (Figure 3d). In fact, there seems to be a strong monotonically increasing dependence of the enhancement factor on the surface-to-volume ratio. The enhanced NPLs also turn out to be extremely stable, as colloidal dispersions retain 90% of their PL intensity after 10 days (cf. Figure S12) and films obtained through spin-coating retained more than 85% of their PL intensity even after continuous illumination with UV-light for 6 h (see Figure S13). Additionally, when investigating the PL lifetimes of the NPL samples, we find that not only does the lifetime increase after the enhancement procedure (e.g. $\tau_{1/e}$ from 1.7 to 4.1 ns for the 3 ML sample), but the shape of the decay also strongly changes (see Figure 3e, cf. Supporting Information including Figures S14 and S15, and Table S2). Although the decay curve of the initial, nonenhanced samples can only be reproduced through a multiexponential function, the decay of all the enhanced NPL samples becomes monoexponential. Finally, we demonstrate that the passivation route can yield blue EL when incorporated in a light-emitting diode (LED) device structure (Figure 3f). The LED device based on the 3 ML NPLs shows pure blue emission with a single, narrow EL peak (fwhm < 20 nm) centered at 464 nm, close to that of the PL (see Supporting Information for more details on the device fabrication and performance, Figure S16). The combination of a narrow emission line width and a pure blue color demonstrate their strong potential for use in high-performance LED applications.^{19,48,49}

To get a deeper understanding of this enhancement procedure, one has to consider that semiconductor NCs are known to be highly prone to surface traps, as the atoms/ions sitting at the edges are undercoordinated, leaving dangling bonds.⁵⁰ For larger perovskite NCs in the unconfined or weakly quantum confined regimes, surface passivation is highly effective, often leading to extremely high PLQY values approaching unity. On the other hand, strongly confined NCs, for example, 2D NPLs, tend to have significantly lower QYs. One reason for this could be due to them possessing a higher surface-to-volume ratio, which could render them more susceptible to surface defects. Additionally, the reduced thickness also leads to a reduced dielectric screening, as witnessed by the strongly increased exciton binding energies. This will likely also increase scattering rates of excitons with defects and polar optical phonons, enhancing nonradiative recombination.²⁸ Such is the case for the NPLs obtained through the synthesis before the enhancement step. As a side note, the enhancement process also works for the nanocubes, even though the enhancement factor is far less due to the extremely high QYs of the initial nanocubes (approximately 92%). This supports the notion of surface traps being the reason for the reduced QYs for thinner NPLs. Interestingly, the shape of the PL decay suggests that the NPLs are split into two subensembles (see Figure 4a). One ensemble without surface defects and a high QY and one ensemble with surface defects and strongly reduced or no emission. The enhancement renders a larger fraction of the NPLs emissive and thus the PL decay becomes dominated by radiative excitonic recombination and not by nonradiative, trap-mediated decay. This also explains why the enhancement is more effective for the thinner NPLs, as surface defects affect them more, increasing the chance that a NPL will be nonemissive.

In order to validate this model and the dramatic increase in the PLQY, we employ differential transmission spectroscopy (DTS). The NPLs in solution are spaced relatively far apart and so do not exchange excited charge carriers. Thus, in solution, each NPL can be considered independent of the other NPLs. If an NPL in the ensemble is photoexcited, it can contain one or multiple electron hole pairs, which rapidly relax down to the 1s exciton state. For the case of multiple excitations, fast nonradiative exciton–exciton annihilation dominates the recombination of the charge carriers^{51,52} until only one exciton per photoexcited NPL remains. In a defect-free NPL, the excited electron hole pair tends to recombine radiatively (light-colored platelet in Figure 4a), whereas the excitation in a NPL with defects has the possibility to recombine radiatively by sending out a photon or nonradiatively via the defect-induced trap states (dark platelet in Figure 4a).

Figure 4b,c shows the steady-state absorption of the 3 ML sample and the respective DTS spectra for an excitation at 400 nm (≈ 3.1 eV) with a dominant bleaching peak at around 452 nm, corresponding to the excitonic peak in the steady state absorption, well below the continuum onset E_C . To study the effect of the postsynthetic enhancement on the dynamics of the differential absorption at the energetic position of the exciton, we look at three different colloidal dispersions of 3 ML NPLs: one before enhancement (initial), one with full enhancement (enhanced), and one where only half the necessary amount of PbBr_2 was added and a reduced enhancement is observed (partially enhanced). Figure 4d,e shows the transients of differential transmission at the

energetic position of the 1s exciton for the initial and the enhanced case.

As proposed above and shown in Figure 4a, we consider there to be two subensembles of NPLs in each sample. As a consequence, the transients in Figure 4d,e represent a superposition of the differential transmission signal of the two subensembles for both cases, the initial and the enhanced sample. As indicated by the black lines, these two transients behave very similar on the very short ($t_{\text{delay}} < 50$ ps) and very long time scales ($t_{\text{delay}} > 500$ ps), however, a significantly different behavior can be observed in the intermediate time regime. With the long time scale process likely being due to recombination, as it is describable through a single exponential function (excitonic recombination), we subtract it from the curves in order to compare the two shorter time scale processes.

After subtracting the late time component, the bleaching decay curves show two main processes happening in the first nanosecond after excitation (see Figure 4f). An initial very fast decay is observed, which we attribute to nonradiative exciton–exciton annihilation, as it exhibits a strong dependency on the excitation density. During the time of the second decay component (50 ps $< t_{\text{delay}} < 500$ ps) a large part of the excitation is lost in the initial sample (dark blue). This amount is substantially reduced in the partially enhanced sample and not observable in the fully enhanced sample. Therefore, we conclude that this decay component stems from a decay channel not present in the enhanced NPLs, namely the nonradiative recombination via surface trap states in the subensemble containing defects. This is strong support for the concept of the reduction of surface traps by postsynthetic enhancement with PbBr_2 , leading to a larger subensemble of defect-free NPLs exhibiting strong radiative recombination.

In conclusion, we have shown a facile synthetic approach to obtain colloidal CsPbBr_3 NPLs with an atomic layer level control of the thickness and with high PLQYs. The NPLs, which range in thickness from 2–6 MLs all exhibit narrow PL emission in the blue color range as well as sharp excitonic absorption peaks. Through linear optical spectroscopy, we confirm that all NPLs lie in the strong quantum confinement regime with exciton binding energies up to 280 meV. The high PLQYs of the NPLs are achieved through a postsynthetic treatment of the NPL dispersions with a PbBr_2 -ligand addition. TR-PL and DTS substantiate our proposition that this strong increase in PL is induced by surface trap repair of bromide and lead vacancies in the NPLs. This is also the reason why the enhancement process affects the thinnest NPLs with a large surface-to-volume ratio in the strongest fashion. This renders the postprocessed colloidal NPLs exhibiting a high PLQY in the range of 50–75%, among the most efficient, tunable blue-emitting perovskites to date. As shown in a proof-of-concept experiment these NPLs could be ideal candidates for blue emitting LEDs, opening the door for all-perovskite white LEDs and other light-emitting applications.

■ ASSOCIATED CONTENT

📄 Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.nanolett.8b02190.

Materials and methods for synthesis and the enhancement procedure. Morphological and structural character-

ization: transmission electron microscopy (TEM), electron diffraction, annual dark-field scanning transmission electron microscopy (ADF-STEM), energy-dispersive X-ray (EDX) spectroscopy, X-ray diffraction (XRD). Optical characterization: UV-vis, PL spectroscopy, time-resolved (TR) PL spectroscopy. LED fabrication and electroluminescence (EL) measurements (PDF)

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Notes

The authors declare no competing financial interest.

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