

NANO EXPRESS

Open Access



Tuning the Optical Properties of CsPbBr₃ Nanocrystals by Anion Exchange Reactions with CsX Aqueous Solution

Anping Yan¹, Yunlan Guo¹, Chao Liu^{1*}, Zhao Deng^{2*}, Yi Guo³ and Xiujuan Zhao^{1*}

Abstract

Topotactic anion exchange has been developed to tune the composition and band gap energies of cesium lead halide (CsPbX₃) perovskite nanocrystals (NCs). However, current anion exchange methods either require harsh conditions or take a long time to realize substantial substitution. Here, we present a method to modulate the composition of colloidal CsPbBr₃ NCs through ultrasonication-assisted anion exchange with CsX (X = Cl, I) solution. Efficient anion exchange of CsPbBr₃ NCs with Cl⁻ or I⁻ is realized with substitution ratio up to 93% and preservation of the pristine shape and structure of CsPbBr₃ NCs. This anion exchange results in tunable emission, covering the whole visible spectral range, with relatively high photoluminescence quantum yield, narrow emission bandwidths, and good stability. This work provides a facile and efficient way to engineer the properties of halide perovskite NCs and has great potential for large-scale production of compositionally diverse perovskite NCs.

Keywords: CsPbBr₃ nanocrystals, Anion exchange, CsX aqueous solution, Ultrasonication, Photoluminescence

Background

All-inorganic CsPbX₃ (X=Cl, Br, and I) perovskite nanocrystals (NCs) have gained significant attention owing to their high photoluminescence (PL) quantum yield (QY) [1], narrow emission line width [2], defect tolerance [3, 4], and wide range of band gaps tunable by control of both composition [5, 6] and morphology [7–9]. The promise of CsPbX₃ NCs has been examined in the context of their applications in optoelectronic devices, such as light-emitting diodes [10–14], Photodetectors [15, 16], lasing [17], and photovoltaics [18, 19].

Especially, the capability of anion exchange of CsPbX₃ NCs has opened the door to many interesting applications of these materials. A broad range of tunable PL from CsPbX₃ NCs could be obtained via a simple post-synthetic procedure, where mixing the solution of NCs with the reactive anion precursors results in the

formation of the anion-exchanged NCs with tunable bandgap [5, 6, 20–22]. The labile nature of the halide anions in the perovskite system is generally responsible for their facile exchange in perovskite NCs and other processes involving ion transport, such as long-range anion diffusion under weak perturbation [23, 24] and the phase segregation in the methylammonium lead-mixed halide system [25]. Due to the simple and wide tunability of the photophysical properties of perovskite NCs, anion exchange has been extensively explored using various sources of anions for different applications [26, 27]. Most of the reported anion exchange methods generally require presynthesized halide precursors, and the reactivity of the halide containing precursors determines the extent and efficiency of the anion exchange. It has been reported that anion exchange of CsPbBr₃ NCs with low-active precursors, such as PbX₂, takes a long time (~1 day or longer) to proceed, and complete exchange of Br anion with X has been shown to be difficult [5]. Halide-containing precursors such as oleylamine halides (OLAM-X) and tetrabutylammonium halides (TBA-X) are highly reactive [5–7], which makes the anion exchange process very efficient, and complete anion exchange can be achieved. However,

* Correspondence: hite@whut.edu.cn; dengzhao@whut.edu.cn; opluse@whut.edu.cn

¹State Key Laboratory of Silicate Materials for Architectures, Wuhan University of Technology, 122 Luoshi Road, Hongshan, Wuhan 430070, China

²State Key Laboratory of Advanced Technology for Materials Synthesis and Processing, Wuhan University of Technology, 122 Luoshi Road, Hongshan, Wuhan 430070, China

Full list of author information is available at the end of the article

these highly reactive precursors are toxic and the anion exchange processes need to be carried out under inert and anhydrous conditions. Therefore, a new method for efficient and green anion exchange of CsPbX_3 NCs is still worth pursuing.

Recently, Yin et al. reported one efficient method to transform the nonluminescent Cs_4PbX_6 NCs into CsPbX_3 NCs [28, 29]. These presynthesized Cs_4PbX_6 NCs were dispersed in nonpolar hexane, and the excess CsX was stripped and dissolved into the water through the interfacial reaction, and further etching of resultant CsPbBr_3 NCs was prohibited by the interface between water and nonpolar solvent. Based on this report, we propose one facile anion exchange method to tune the composition and optical properties of the CsPbBr_3 NCs. The presynthesized CsPbBr_3 NCs are dispersed in hexane, and the anion exchange is realized through the interfacial reaction with CsX ($X=\text{Cl}, \text{I}$) aqueous solution assisted by ultrasonication. The extent and rate of the anion exchange reaction are controlled by ultrasonic time and CsX concentration. Compared to most of the reported anion exchange methods [5–7, 20–22], this anion exchange scheme is very facile and environment-friendly. The halide precursors for anion exchange can be dissolved into water instead of organic solution, and after anion exchange, halides dissolved in water can be easily separated by desiccation. Most importantly, the reaction can be carried out under normal condition, instead of the inert and anhydrous conditions. The proposed mechanism of the anion exchange of CsPbX_3 NCs in CsX aqueous solutions is illustrated in Fig. 1 Br^- ions in the CsPbBr_3 NCs exchanges with the Cl^- or I^- ions, resulting in the formation of CsPbX_3 NCs. By adjusting the reaction time or the CsX aqueous solution, complete tunable composition of CsPbX_3 NCs and emission covering the full

visible spectral range with narrow band widths can be achieved.

Methods

Synthesis and Purification of CsPbBr_3 NCs

CsPbBr_3 NCs are synthesized following the method reported by Protesescu et al. [1]. In a typical experiment, 0.8 g of Cs_2CO_3 (99.9%, Aldrich), 2.5 ml of oleic acid (OA; 90%, Aldrich) and 30 ml of octadecene (ODE; 90%, Aldrich) are added into a 100-ml 3-neck flask, degassed at room temperature for 30 min, and then dried for 1 h at 120 °C under Ar until all Cs_2CO_3 reacted with OA. 0.136 g of PbBr_2 (99.9%, Aldrich), 2 mL of oleylamine (OALM; Aldrich, 80–90%), 1.5 mL of OA, and 8 mL ODE are added to a 25-mL 3-neck round bottom flask. The solution is evacuated and refilled with Ar followed by heating to 120 °C for 30 min. The solution is heated to 180 °C and kept for another 10 min. Then the Cs-oleate (1 mL) is injected and after 10 s the solution is cooled with an ice bath. The NCs are precipitated with acetone (AR, Sinopharm) and then centrifuged followed by dissolving in hexanes (AR, Sinopharm).

Anion Exchange Reactions

5-ml of CsX (1 mol/L, 0.2 mol/L, $X=\text{Cl}, \text{I}$) aqueous solution is loaded in a 25-mL glass bottle and 3 ml of CsPbBr_3 NCs/hexane solution (4.5 mmol/L in Br^-) is dropped inside, and then by bath-sonication (KQ-50B, ultrasonic cleaner) at a power of 50 W (total power) for some time. After ultrasonication, the system is then kept undisturbed for 5 min, and then the organic phase layer is collected (CsX aqueous solution can be reused by purification). Afterwards, the product is centrifuged at 2500 rpm for 5 min to discard the precipitates.

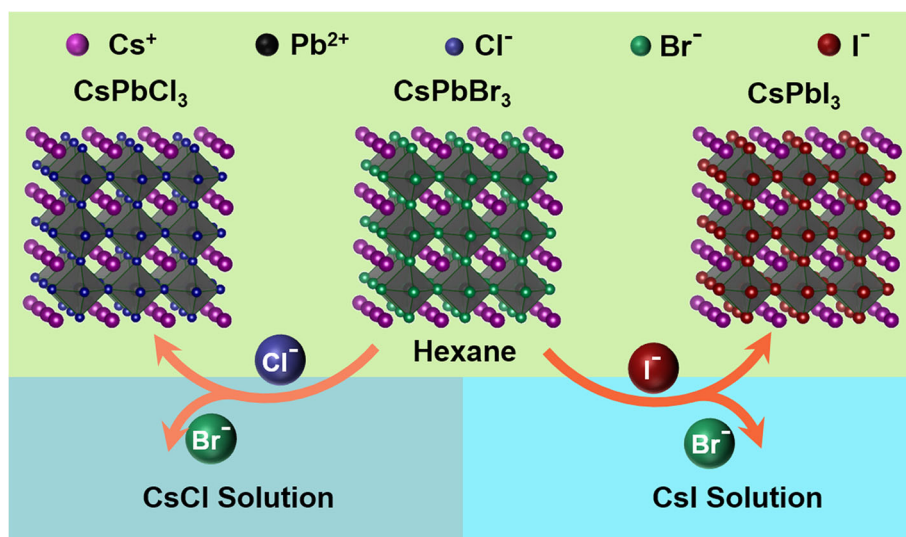


Fig. 1 Illustration of the mechanism for anion exchange of perovskite nanocrystals in aqueous solutions

Characterization

The phases of the products are examined by X-ray powder diffractometer (D8 Advance, Bruker) and high-resolution transmission electron microscope (HR-TEM, JEM 2100F, JEOL, Japan) operating at 200 kV. Absorption spectra of the colloidal CsPbX₃ NCs are recorded using an UV/Vis/NIR spectrophotometer (UV3600, Shimadzu, Japan).

Photoluminescence Measurements

Photoluminescence (PL) spectra of the colloidal CsPbX₃ NCs are collected by a Photo Technology International (PTI) QM/TM/NIR spectrophotometer with a 914 photomultiplier detection system and using a 75-W xenon lamp as the excitation source. All the optical measurements are carried out at room temperature. 400 nm of light is used as the excitation source for all the CsPbX₃ NCs, except 360 nm for CsPb(Br/Cl)₃ NCs. Following the method proposed by Prato et al. [5], four measurements are performed for PLQY: (i) the sample emission (SEM) that collects the photons emitted by the sample, (ii) the blank emission (BEM), which is a measurement performed with the cuvette containing only the solvent (blank) in the same spectral range used for the SEM measurement, (iii) the sample excitation (SEX), which records the photons at the pumping wavelength that are not absorbed by the sample, and (iv) the blank excitation (BEX), which records the photons at the pumping wavelength going through the blank. The photoluminescence quantum yield PLQY is then calculated as

$$\text{PLQY}(\%) = \frac{\text{SEM}-\text{BEM}}{\text{BEX}-\text{SEX}} \times 100$$

Any reabsorption correction factor is neglected in our calculation of the PLQY, since the solutions investigated are diluted to the point that reabsorption of the PL could be neglected.

Stability Test

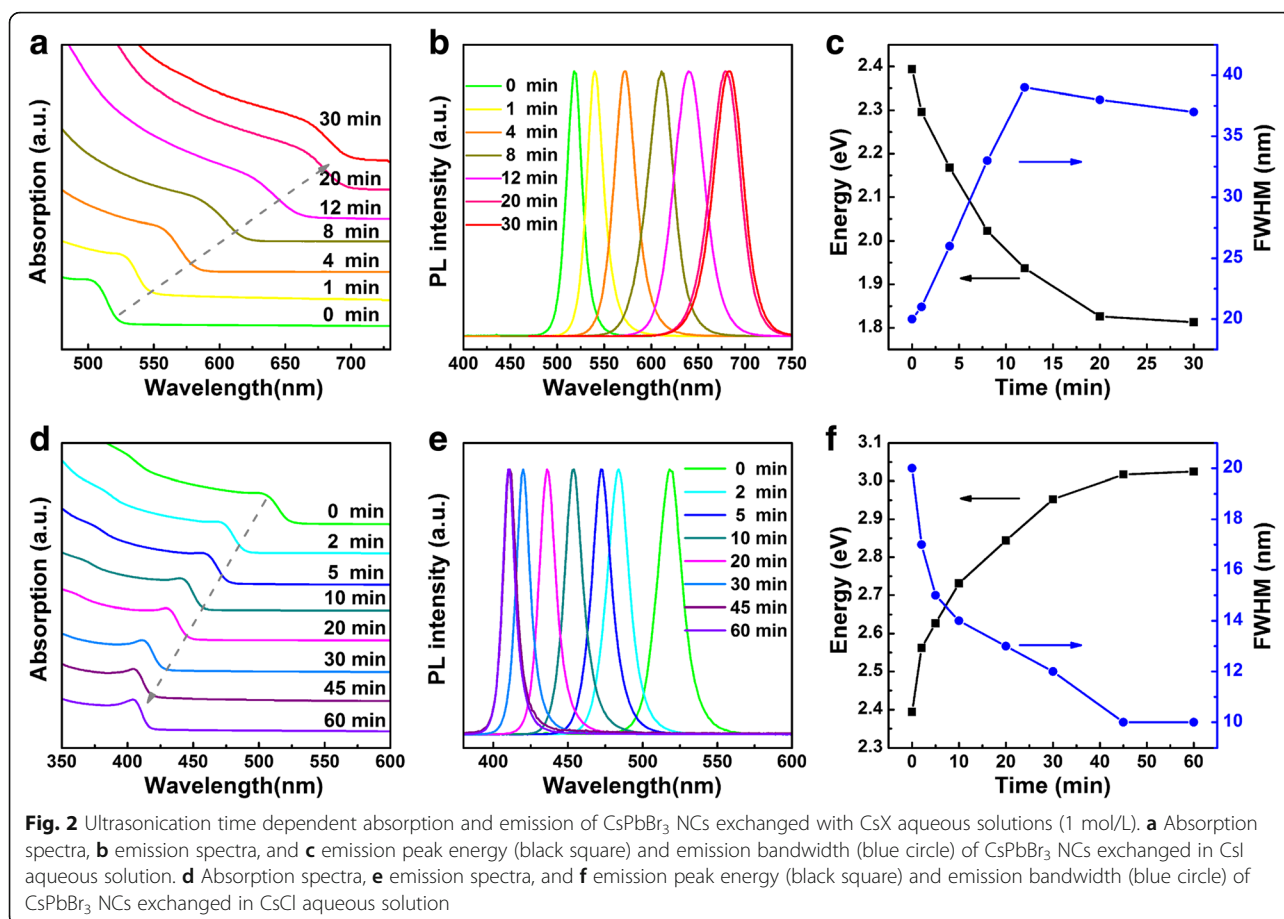
The perovskite NCs are dispersed in hexane and sealed into glass bottles, which are kept under ambient condition for several weeks. Changes in the absorption and PL of these anion-exchanged perovskite NCs are recorded at an interval of 7 days.

Results and Discussion

Figure 2 summarizes the continuous changes in the absorption and emission spectra of mixed anion CsPbX₃ NCs obtained through ion-exchange with CsI aqueous solution (Fig. 2a, b) and CsCl aqueous solution (Fig. 2d, e). The time-trace and full width at half maximum (FWHM) of the emission peaks are also shown

for both reactions (Fig. 2c, f). Absorption and emission peaks of CsPbX₃ NCs showed obvious red shift with anion exchange with CsI solution, indicating the exchange of bromide with iodide and formation of CsPb(Br/I)₃ NCs. Upon 30-min ultrasonication, absorption and emission peaks stabilize at 675 nm (Fig. 2a) and 685 nm (Fig. 2b), respectively. With CsCl solution, both absorption and emission peaks of CsPb(Br/Cl)₃ NCs show gradual blue shift upon continuous ultrasonication. With ultrasonication, the absorption peak shifts to 405 nm (Fig. 2d) and the emission peak shifts to 411 nm (Fig. 2e) within 45 min and stabilizes. This process allows the formation of CsPbX₃ NCs with tunable band gap energies (Fig. 2c, f) and emission spanning over the whole visible spectral range. It has to be pointed out that the FWHM of CsPb(Br/I)₃ NCs gradually increases from 20 nm to a maximal value of 39 nm (Fig. 2c), while the FWHM of CsPb(Br/Cl)₃ NCs monotonically decreased from 20 to 10 nm (Fig. 2f). These changes in the FWHM values show that the size dispersion of the pristine CsPbBr₃ NCs is largely maintained.

Emission photograph of the anion-exchanged perovskite NCs is shown in Fig. 3a. Upon exchange with CsCl or CsI aqueous solution, emission color of the NCs gradually changes to blue or red. Most importantly, size and morphology of the CsPbBr₃ NCs template are preserved during the anion-exchange process (Fig. 3b–d). As confirmed by the TEM images, after the anion exchange, average sizes of CsPb(Br/Cl)₃ NCs with sonication time of 60 min (Fig. 3b) and CsPb(Br/I)₃ NCs with sonication time of 30 min (Fig. 3d) are almost the same as the pristine CsPbBr₃ NCs (Fig. 3c), and the shape still remains as cubic. CsPbX₃ NCs obtained with other sonication time (Additional file 1: Figure S1 for CsI aqueous solution and Additional file 1: Figure S3 for CsCl aqueous solution) show the same cubic shape, although after exchange of Br⁻ ions with I⁻ ions their size increased slightly from (9.6 ± 1.3) to (11.1 ± 1.5) nm (Additional file 1: Figure S2), whereas the exchange with Cl⁻ ions led to a slight decrease in size, to (8.2 ± 1.4) nm (Additional file 1: Figure S4). The selected area electron diffraction pattern (Additional file 1: Figure S5) confirms that these CsPbBr₃ NCs and exchanged CsPbX₃ NCs all had the same cubic structure with space group of *Pm* $\bar{3}$ *m* (221). The HR-TEM images (Fig. 3e–f) evidenced the high quality of the pristine CsPbBr₃ NCs (Fig. 3f), the exchanged CsPb(Br/Cl)₃ NCs (Fig. 3e) and CsPb(Br/I)₃ NCs (Fig. 3g). These results show that the anion exchange with CsX aqueous solution does not deteriorate or etch the perovskite NCs. Successful exchange of Br⁻ ions with Cl⁻ or I⁻ ions is further confirmed by the changes in the lattice distance shown in Fig. 3e–g. For the perovskite NCs obtained through exchange with CsCl aqueous solution for 60 min, the



(100) lattice constant is found to be 0.56 nm, almost identical to that of CsPbCl₃ NCs (JCPDF No.: 75-0411). For those NCs exchanged with CsI aqueous solution for 30 min, the (100) lattice constant increases from 0.583 nm of CsPbBr₃ NCs (JCPDF No.: 54-0752) to 0.615 nm, close to that of CsPbI₃ NCs [5–7]. For CsPb(Br/I)₃ NCs, the (100) lattice plane distance increases from 0.583 nm of CsPbBr₃ NCs to 0.591, 0.6, and 0.615 nm as the sonication time increases from 0 to 4, 8, and 30 min, respectively (Additional file 1: Figure S1). For CsPb(Br/Cl)₃ NCs, the (100) lattice plane distance decreased from 0.583 nm of CsPbBr₃ NCs to 0.575, 0.57, and 0.561 nm, as the sonication time increases from 0 to 5, 10, and 60 min, respectively (Additional file 1: Figure S3). X-ray diffraction pattern also shows that all the diffraction peaks of the CsPbX₃ NCs can be assigned to cubic perovskite, and they gradually shift towards higher angles approaching that of CsPbCl₃ NCs, and lower angles approaching that of CsPbI₃ NCs when exchanged with CsCl and CsI aqueous solution, respectively (Additional file 1: Figure S6).

Actual compositions of the exchanged perovskite NCs analyzed using energy dispersive X-ray spectroscopy (EDX) are listed in Table 1, along with the measured

PLQY and emission peak energy. With continuous anion exchange with CsX aqueous solution, the Br⁻ to Cl⁻ substitution ratio can reach 93% in CsPb(Br/Cl)₃ NCs, and the Br⁻ to I⁻ substitution ratio can reach 90%. These substitution ratios are comparable to those achieved with highly reactive precursors such as OLAM-X and TBA-X [5–8], demonstrating that anion exchange through CsX aqueous solution was also a powerful route to tune the chemical composition of CsPbX₃ NCs. With anion exchange, the PLQY of CsPb(Br/Cl)₃ NCs firstly increases from 76% of the pristine CsPbBr₃ NCs to 85% of the CsPbBr_{2.3}Cl_{0.7} NCs, and then rapidly drops to 32% (CsPbBr_{2.0}Cl_{1.0} NCs) and 5% (CsPbBr_{0.2}Cl_{2.8} NCs). The PLQY of the CsPb(Br/I)₃ NCs monotonically declines from 76% of the pristine CsPbBr₃ NCs to 31% of CsPbBr_{0.3}I_{2.7} NCs. This trend is in line with that reported by Pellet et al. [30]. It has to be pointed out that PLQY of the CsPbX₃ NCs obtained through the longest sonication is comparable to those of directly synthesized CsPbI₃ and CsPbCl₃ NCs [30–32], further confirming that anion exchanged through CsX aqueous solution does not lead to the deterioration of the optical properties of the CsPbX₃ NCs. Even though these CsPbX₃ NCs are exchanged with aqueous solution, they still maintain

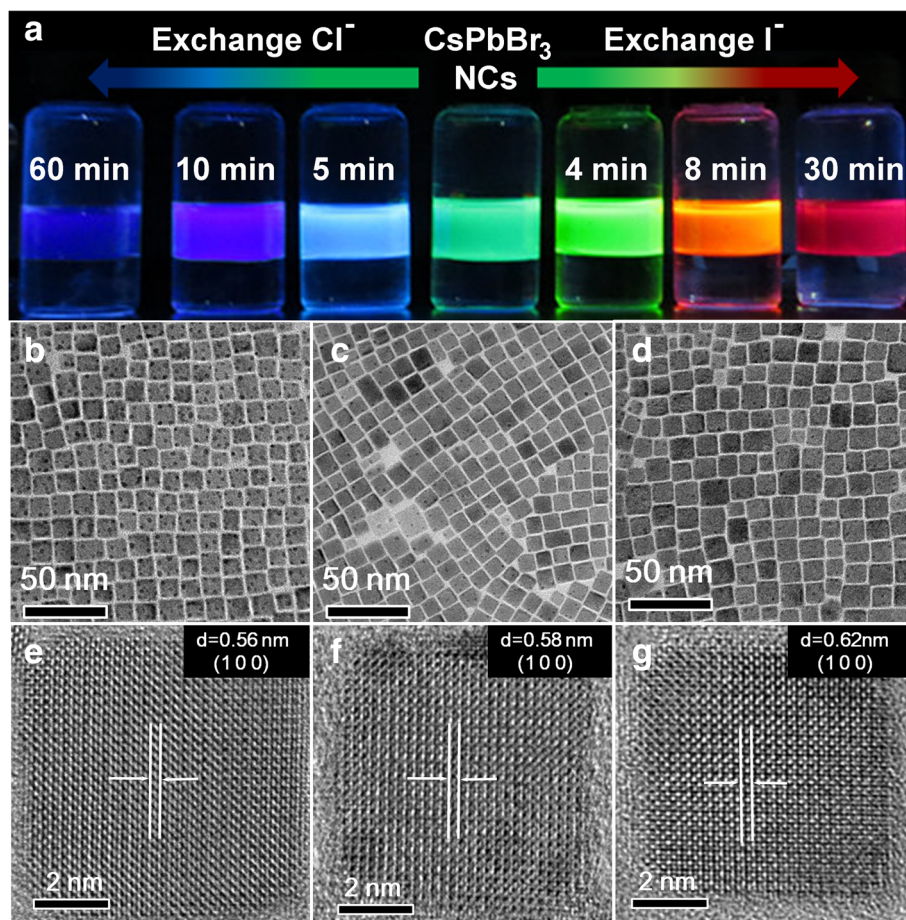


Fig. 3 a Emission photograph of perovskite NCs exchanged with 1 mol/L CsX aqueous solution under 365-nm light illumination. TEM and HR-TEM images of CsPb(Br/Cl)₃ NCs obtained from 60 min exchange (**b, e**), pristine CsPbBr₃ NCs (**c, f**), and CsPb(Br/I)₃ NCs obtained from 30 min exchange (**d, g**)

relative good room temperature stability when stored in hexane, mainly due to the low solubility of water in hexane (9.5 mg/L) [28]. For CsPb(Br/Cl)₃ NCs obtained through 45 min sonication, the PL intensity decreased to ~30% of the original intensities within 4 weeks (Additional file 1: Figure S7a). While for CsPb(Br/I)₃ NCs obtained through 20 min sonication, only 5% of the

original PL intensities was retained within 4 weeks (Additional file 1: Figure S7b).

This facile ultrasonication-assisted anion exchange with CsX aqueous solution is mainly driven by the large concentration of CsX in the aqueous solution. Anion-exchange of CsPbBr₃ NCs with octadecylamine halides (ODA-X) and lead halides (PbX₂) salts was found to be slow and incomplete [5], due to the low solubility of these compounds in the nonpolar toluene solvent. The relatively large solubility of OLAM-X and TBA-X in toluene makes the anion exchange of CsPbBr₃ NCs very fast and complete [5–8]. The fast anion exchange and wide tunable spectral range of absorption and emission reported in this work are mainly ascribed to the large solubility of CsX in water (1865 g/L for CsCl and 440 g/L for CsI in water) [28], which provide the large driving force for the anion exchange. To further confirm the effect of CsX aqueous solution concentration on the anion exchange of CsPbX₃ NCs, CsPbBr₃ NCs are exchanged with CsX aqueous solution of 0.2 mol/L (Fig. 4). It is

Table 1 Composition, emission energy, and PLQY of CsPbBr₃NCs exchanged under different conditions

Aqueous solution	Sonication time (min)	EDX composition	PL energy (eV)	PL QYs (%)
1 mol/L CsCl	60	CsPbBr _{0.2} Cl _{2.8}	3.04	5
	10	CsPbBr _{2.0} Cl _{1.0}	2.74	32
	5	CsPbBr _{2.3} Cl _{0.7}	2.62	85
Pristine	0	CsPbBr ₃	2.39	76
1 mol/L CsI	4	CsPbBr _{2.5} I _{0.5}	2.25	52
	8	CsPbBr _{2.2} I _{0.8}	2.03	46
	30	CsPbBr _{0.3} I _{2.7}	1.83	31

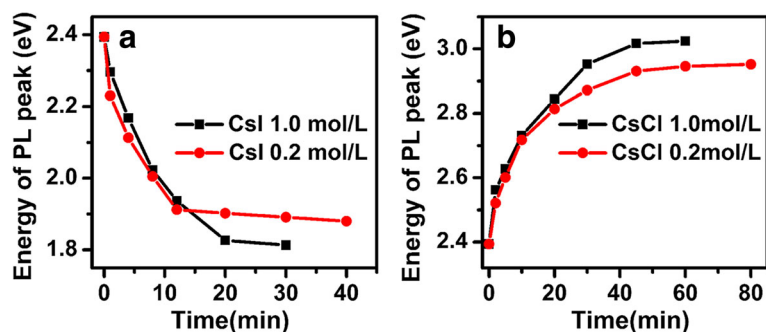


Fig. 4 Emission peak energies of CsPbX₃ NCs exchanged with 1.0 and 0.2 mol/L **a** CsI and **b** CsCl aqueous solution

found that the PL peak energy of CsPb(Br/I)₃ NCs gradually stabilized at 1.88 eV (Fig. 4a) with 40-min sonication, and the PL peak energy of CsPb(Br/Cl)₃ NCs gradually approaches at 2.95 eV (Fig. 4b) even with 80-min ultrasonication. The ultrasonication time dependence of the emission peak energy shows that concentration of the CsX aqueous solution does not affect the speed at the early stage, but determines the final composition of the CsPbX₃ NCs, providing a new route to precisely control the composition of the exchanged CsPbX₃ NCs.

Conclusions

In conclusion, we report here a simple and environment-friendly ultrasonication assisted anion-exchange of CsPbBr₃ NCs with CsX aqueous solution. This anion-exchange happens at the interface of the CsX aqueous solution and hexane. By carefully selecting the anion-exchange condition, more than 90% of the Br⁻ ions in CsPbBr₃ NCs can be substituted by X⁻ ions, while maintaining the shape and structure of the pristine CsPbBr₃ NCs. Both absorption and emission of these exchanged CsPbX₃ NCs can span the full visible spectral range, with a relatively high PLQY and stability. This anion-exchange method provides another facile route to modulate the chemical compositions and optical properties of CsPbX₃ NCs.

Additional file

Additional file 1: Additional XRD patterns, TEM images, and PL spectra (DOCX 4026 kb)

Abbreviations

EDX: Energy-dispersive X-ray spectroscopy; NCs: Nanocrystals; OA: Oleic acid; OALM: Oleylamine; ODE: Octadecene; PL: Photoluminescence; TBA: Tetrabutylammonium; TEM: Transmission electron microscope; XRD: X-ray diffraction

Funding

This work was supported by the Funds for Creative Research Group of Hubei Province (2018CFA005) and the Open Fund of the State Key Laboratory of

Luminescent Materials and Devices (2018-skllmd-04, South China University of Technology).

Availability of Data and Materials

The datasets generated during and/or analyzed during the current study are available from the corresponding authors on reasonable request.

Authors' Contributions

LC and ZX conceived and designed the experiments. YA and GY carried out the experiments. YA and LC co-wrote the manuscript. DZ and GY performed the TEM experiments. All authors contributed to data analysis and scientific discussion. All authors read and approved the final manuscript.

Competing Interests

The authors declare that they have no competing interests.

Publisher's Note

Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Author details

¹State Key Laboratory of Silicate Materials for Architectures, Wuhan University of Technology, 122 Luoshi Road, Hongshan, Wuhan 430070, China. ²State Key Laboratory of Advanced Technology for Materials Synthesis and Processing, Wuhan University of Technology, 122 Luoshi Road, Hongshan, Wuhan 430070, China. ³Materials Research and Test Center, Wuhan University of Technology, 122 Luoshi Road, Hongshan, Wuhan 430070, China.

Received: 12 March 2018 Accepted: 5 June 2018

Published online: 20 June 2018

References

- Protesescu L, Yakunin S, Bodnarchuk MI, Krieg F, Caputo R, Hendon CH, Yang RX, Walsh A, Kovalenko MV (2015) Nanocrystals of cesium lead halide perovskites (CsPbX₃, X = Cl, Br, and I): novel optoelectronic materials showing bright emission with wide color gamut. *Nano Lett* 15:3692–3696
- Swarnkar A, Chulliyil R, Ravi VK, Irfanullah M, Chowdhury A, Nag A (2016) Colloidal CsPbBr₃ perovskite nanocrystals: luminescence beyond traditional quantum dots. *Angew Chem* 127:15644–15648
- Brandt RE, Stevanović V, Ginley DS, Buonassisi T (2015) Identifying defect-tolerant semiconductors with high minority-carrier lifetimes: beyond hybrid lead halide perovskites. *MRS Commun* 5:265–275
- Dirin DN, Protesescu L, Trummer D, Kochetygov IV, Yakunin S, Krumeich F, Stadie NP, Kovalenko MV (2016) Harnessing defect-tolerance at the nanoscale: highly luminescent lead halide perovskite nanocrystals in mesoporous silica matrices. *Nano Lett* 16:5866–5874
- Akkerman QA, D'Innocenzo V, Accornero S, Scarpellini A, Petrozza A, Prato M, Manna L (2015) Tuning the optical properties of cesium lead halide perovskite nanocrystals by anion exchange reactions. *J Am Chem Soc* 137:10276–10281
- Nedelcu G, Protesescu L, Yakunin S, Bodnarchuk MI, Grotevent MJ, Kovalenko MV (2015) Fast anion-exchange in highly luminescent

- nanocrystals of cesium lead halide perovskites (CsPbX_3 , $X = \text{Cl, Br, I}$). *Nano Lett* 15:5635–5640
7. Bekenstein Y, Koscher BA, Eaton SW, Yang P, Alivisatos AP (2015) Highly luminescent colloidal nanoplates of perovskite cesium lead halide and their oriented assemblies. *J Am Chem Soc* 137:16008–16011
 8. Zhang D, Yu Y, Bekenstein Y, Wong AB, Alivisatos AP, Yang P (2016) Ultrathin colloidal cesium lead halide perovskite nanowires. *J Am Chem Soc* 138:13155–13158
 9. Fang F, Chen W, Li Y, Liu H, Mei M, Zhang R, Hao J, Mikita M, Cao W, Pan R, Wang K, Sun X (2018) Employing polar solvent controlled ionization in precursors for synthesis of high-quality inorganic perovskite nanocrystals at room temperature. *Adv Funct Mater* 28:1706000
 10. Zhang X, Lin H, Huang H, Reckmeier C, Zhang Y, Choy WC, Rogach AL (2016) Enhancing the brightness of cesium lead halide perovskite nanocrystal based green light-emitting devices through the interface engineering with perfluorinated ionomer. *Nano Lett* 16:1415–1420
 11. Song J, Li J, Li X, Xu L, Dong Y, Zeng H (2015) Quantum dot light-emitting diodes based on inorganic perovskite cesium lead halides (CsPbX_3). *Adv Mater* 27:7162–7167
 12. Li X, Wu Y, Zhang S, Cai B, Gu Y, Song J, Zeng H (2016) CsPbX_3 quantum dots for lighting and displays: room-temperature synthesis, photoluminescence superiorities, underlying origins and white light-emitting diodes. *Adv Funct Mater* 26:2435–2445
 13. Li J, Xu L, Wang T, Song J, Chen J, Xue J, Dong Y, Cai B, Shan Q, Han B, Zeng H (2017) 50-fold EQE improvement up to 6.27% of solution-processed all-inorganic perovskite CsPbBr_3 QLEDs via surface ligand density control. *Adv Mater* 29:1603885–1603893
 14. Yang D, Zou Y, Li P, Liu Q, Wu L, Hu H, Xu Y, Sun B, Zhang Q, Lee S-T (2018) Large-scale synthesis of ultrathin cesium lead bromide perovskite nanoplates with precisely tunable dimensions and their application in blue light-emitting diodes. *Nano Energy* 47:235–242
 15. Song J, Xu L, Li J, Xue J, Dong Y, Li X, Zeng H (2016) Monolayer and few-layer all-inorganic perovskites as a new family of two-dimensional semiconductors for printable optoelectronic devices. *Adv Mater* 28:4861–4869
 16. Dong Y, Gu Y, Zou Y, Song J, Xu L, Li J, Xue J, Li X, Zeng H (2016) Improving all-inorganic perovskite photodetectors by preferred orientation and plasmonic effect. *Small* 12:5622–5632
 17. Wang Y, Li X, Song J, Xiao L, Zeng H, Sun H (2015) All-inorganic colloidal perovskite quantum dots: a new class of lasing materials with favorable characteristics. *Adv Mater* 27:7101–7108
 18. Swarnkar A, Marshall AR, Sanhira EM, Chernomordik BD, Moore DT, Christians JA, Chakrabarti T, Luther JM (2016) Quantum dot-induced phase stabilization of α - CsPbI_3 perovskite for high-efficiency photovoltaics. *Science* 354:92–95
 19. Akkerman QA, Gandini M, Di Stasio F, Rastogi P, Palazon F, Bertoni G, Ball JM, Prato M, Petrozza A, Manna L (2016) Strongly emissive perovskite nanocrystal inks for high-voltage solar cells. *Nat Energy* 2:16194–16200
 20. Yoon SJ, Draguta S, Manser JS, Sharia O, Schneider WF, Kuno M, Kamat PV (2016) Tracking iodide and bromide ion segregation in mixed halide lead perovskites during photoirradiation. *ACS Energy Lett* 1:290
 21. Koscher BA, Bronstein ND, Olshansky JH, Bekenstein Y, Alivisatos AP (2016) Surface-vs diffusion-limited mechanisms of anion exchange in CsPbBr_3 nanocrystal cubes revealed through kinetic studies. *J Am Chem Soc* 138:12065–12068
 22. Parobek D, Dong Y, Qiao T, Son D (2017) Photoinduced anion exchange in cesium lead halide perovskite nanocrystals. *J Am Chem Soc* 139:4358–4361
 23. Eames C, Frost JM, Barnes PR, O'Regan BC, Walsh A, Islam MS (2015) Ionic transport in hybrid lead iodide perovskite solar cells. *Nat Commun* 6:7497
 24. Azpiroz JM, Mosconi E, Bisquert J, De Angelis F (2015) Defect migration in methylammonium lead iodide and its role in perovskite solar cell operation. *Energy Environ Sci* 8:2118–2127
 25. Hoke ET, Slotcavage DJ, Dohner ER, Bowring AR, Karunadasa HI, McGehee MD (2015) Reversible photo-induced trap formation in mixed-halide hybrid perovskites for photovoltaics. *Chem Sci* 6:613–617
 26. Palazon F, Akkerman QA, Prato M, Manna L (2016) X-ray lithography on perovskite nanocrystals films: from patterning with anion-exchange reactions to enhanced stability in air and water. *ACS Nano* 10:1224–1230
 27. Doane TL, Ryan KL, Pathade L, Cruz KJ, Zang H, Cotlet M, Maye MM (2016) Using perovskite nanoparticles as halide reservoirs in catalysis and as spectrochemical probes of ions in solution. *ACS Nano* 10:5864–5872
 28. Wu L, Hu H, Xu Y, Jiang S, Chen M, Zhong Q, Yang D, Liu Q, Zhao Y, Sun B, Zhang Q, Yin Y (2017) From nonluminescent Cs_4PbX_6 ($X = \text{Cl, Br, I}$) nanocrystals to highly luminescent CsPbX_3 nanocrystals: water-triggered transformation through a CsX-stripping mechanism. *Nano Lett* 17:5799–5804
 29. Hu H, Wu L, Tan Y, Zhong Q, Chen M, Qiu Y, Yang D, Sun B, Zhang Q, Yin Y (2018) Interfacial synthesis of highly stable CsPbX_3 /oxide Janus nanoparticles. *J Am Chem Soc* 140(1):406–412
 30. Pellet N, Teuscher J, Maier J, Grätzel M (2015) Transforming hybrid organic inorganic perovskites by rapid halide exchange. *Chem Mater* 27:2181–2188
 31. Xing G, Mathews N, Lim SS, Yantara N, Liu X, Sabba D, Grätzel M, Mhaisalkar S, Sun TC (2014) Low-temperature solution-processed wavelength-tunable perovskites for lasing. *Nat Mater* 13:476–480
 32. Stranks SD, Burlakov VM, Leijtens T, Ball JM, Goriely A, Snaith H (2014) Recombination kinetics in organic-inorganic perovskites: excitons, free charge, and subgap states. *Phys Rev Appl* 2:034007

Submit your manuscript to a SpringerOpen[®] journal and benefit from:

- Convenient online submission
- Rigorous peer review
- Open access: articles freely available online
- High visibility within the field
- Retaining the copyright to your article

Submit your next manuscript at ► springeropen.com
