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Energy Transfer between Inorganic Perovskite Nanocrystals

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Supporting Information

ABSTRACT: Cesium lead halide nanocrystals are a new attractive material for optoelectronic applications since they combine the advantageous properties of perovskites and quantum dots. For future applications in optoelectronics and photovoltaics, an efficient energy and/or carrier exchange is a necessary condition. Here, we explicitly demonstrate nonradiative energy transfer for colloidal CsPbBr3 nanocrystals. Using time-resolved optical characterization of purposefully prepared batches of nanocrystals with different sizes, we identify the energy transfer which can be driven by the concentration gradient of excited nanocrystals as well as by the bandgap energy difference. The latter process moves the energy from smaller to larger nanocrystals and opens a possibility of directional streaming of the excitation energy in these materials. The observed energy transfer is enabled in the colloids by proximity of individual nanocrystals due to clustering.

1. INTRODUCTION

Metal halide semiconductors with perovskite structure have attracted much interest in the past years due to their high emission efficiencies and low production costs, making them attractive for photovoltaic and optoelectronic applications.1,2 Most of the progress in this research area has been focused on hybrid organic–inorganic perovskites3−5 (e.g., CH3NH3PbI3, CH3NH3PbBr3, CH3NH3PbI3Br, etc.) as a solid state material supported on a substrate, with grain sizes outside of the nanoscale. On the other hand, colloidal semiconductor nanocrystals (NCs)6−8 (e.g., CdSe, CdTe, PbS, etc.) have also been widely studied as optoelectronic materials because their optical properties are enhanced by quantum-confinement effects.9−12 The advantages of using semiconductor perovskites and NCs are combined in the colloidal inorganic cesium lead halide NCs (CsPbX3, X = Cl, Br, and I) with cubic perovskite structure. They were first synthesized by Protesescu et al.13 and their photoluminescence (PL) is characterized by narrow emission bands and high quantum yields (QYs) of 50−90%. The novelty of this material has driven many investigations during the past year, for instance studies of air stability,14,15 optical properties,16,17 and lasing.18−20 To design efficient optoelectronic devices based on semiconductor NCs,21,22 the interaction between individual NCs needs to be evaluated and possibly engineered. In particular, for photovoltaic cells, an exciton generated upon photon absorption needs to be either separated into an electron and a hole pair and the free carriers are transported toward the respective electrodes (semiconductor cells)23 or moved toward an interface and be split there (polymer cells).24 In general, there are three possible mechanisms of exciton transfer:25 cascade energy transfer (involving emission and subsequent reabsorption of a photon), Dexter transfer (involving electron exchange interactions), and Förster resonance energy transfer (FRET), mediated by Coulomb interactions between a donor and acceptor. Here, we explore the energy transfer (ET) between NCs, from a donor to an acceptor with a lower bandgap energy. ET between direct bandgap semiconductor NCs is typically described by FRET,26 which depends on the spectral overlap of donor emission and acceptor absorption, and the donor−acceptor Coulomb coupling, determined by the distance between them. ET in closed-packed ensembles of NCs of direct bandgap semiconductors (CdSe, CdTe, PbS, InP, etc.) has been demonstrated in the past by means of changes in the PL spectra and lifetimes.27−30 Also, the energy exchange between NCs of silicon, the most widely used material for photovoltaics and electronics, has been conclusively established.31,32 In hybrid perovskite-based solar cells, energy exchange has just been observed between perovskite films and layers of organic electron and hole acceptors33,34 and a so-called “dots-in-a-matrix” using PbS NCs.35 Accordingly, also exciton transfer between perovskite NCs could be expected but has not been shown until now. To the contrary, a recent study on perovskite NC films revealed no evidence of ET.36 While this negative
result was tentatively explained by large sizes of the investigated materials, the urgent need for further research appeared. In this work, we investigate ET between cesium lead bromide (CsPbBr₃) all-inorganic NCs with perovskite structure in colloidal state and provide explicit and conclusive evidence of effective ET proceeding from small to large NCs. We show that the ET process in the investigated colloids is enabled by clustering which brings the NCs in direct contact.

2. EXPERIMENTAL SECTION

Materials. Cesium carbonate (Cs₂CO₃, 99.9%, Sigma-Aldrich), octadecene (ODE, 90%, Sigma-Aldrich), oleic acid (OA, 90%, Sigma-Aldrich), oleylamine (OLA, 80–90%, Acros), lead(II) bromide (PbBr₂, 98%, Sigma-Aldrich), and toluene (ACS reagent, ≥99.5%, Sigma-Aldrich) were used with no further purification, except for the drying period reported in the synthesis procedure.

Synthesis. Cesium lead bromide perovskites (CsPbBr₃) were synthesized as described by Proteșescu et al. Summarizing, 5 mL of ODE and 70 mg of PbBr₂ were dried for 1 h at 120 °C under a N₂ atmosphere. After water removal, 0.5 mL of dried OLA and 0.5 mL of dried OA were added to the reaction flask, and the temperature was raised up to the desired value. After complete solvation of the PbBr₂ salt, 0.4 mL of a previously synthesized Cs-oleate solution in ODE was injected. A few seconds later, the NC solution was quickly cooled down with an ice bath. The product was purified by centrifugation and redispersion in toluene. The perovskite synthesis was carried out at two different temperatures, yielding different NC sizes as described in the literature. The samples that were studied have a concentration of 0.2 mg/mL, as determined from the dry weight.

Characterization. The optical density of the investigated colloids was measured in a LAMBDA 950 UV/vis/NIR spectrophotometer (PerkinElmer). A combination of a tungsten–halogen and deuterium lamp is used together with a PMT and Peltier cooled PbS detector to provide a detection range of $E_{det} = 5.6–0.4$ eV. The sample and solvent measurements have been performed separately and afterward subtracted from each other. The PL has been studied under excitation energy $E_x$ (OA, 90%, Sigma-Aldrich), oleylamine (OLA, 80–90%, Acros), lead(II) bromide (PbBr₂, 98%, Sigma-Aldrich), and toluene (ACS reagent, ≥99.5%, Sigma-Aldrich) were used with no further purification, except for the drying period reported in the synthesis procedure.

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The PL emission and excitation light are scattered coupled to a spectrometer (Solar, MSA-130) as an excitation source. The PL emission has been detected using a monochromator (Newport CS260-02) coupled to a PMT (Hamamatsu) providing a total detection range of $E_{det} = 6–1.6$ eV. The overall instrument response function (IRF) is 20–25 ps (fwhm) as measured from a dilute scattering solution (Ludox) at the excitation wave-length. All measurements have been performed at room temperature.

3. RESULTS AND DISCUSSION

The colloidal synthesis yields near-monodisperse CsPbBr₃ NCs with a cubic perovskite structure whose size, and therefore PL emission energy, can be tuned between approximately 2.3 and 2.7 eV by controlling the temperature at which the synthesis is performed. Figure 1 shows the optical characterization (see also Figure S1 in the Supporting Information) and TEM images for the materials used in this study (samples A and B). The PL bands (Figure 1a) centered at 2.43 and 2.36 eV for samples A and B with full widths at half-maximum of 0.1 and 0.089 eV, respectively, show a small Stokes shift from their corresponding absorption spectra that exhibit a clear excitonic peak at the onset. The inset shows the samples under UV illumination indicating that they are similarly bright to the eye; a minor difference in color can hardly be distinguished. We have determined a PL quantum yield of ~90% and ~30% for samples A and B, respectively. The TEM images with their corresponding histograms (Figures 1b–e) confirm the formation of cubic NCs with an average edge size of 8.4 ± 1.4 nm (b, c) and 18.3 ± 2.8 nm (d, e), respectively. Note that synthesis at a higher temperature (sample B) leads to a larger size distribution of the NCs and an occasional shape deformation. A similar PL line width of both samples A and B (Figure 1a) in spite of the significantly broader size distribution of sample B (Figures 1c,e) is the first indication of a possible excitation flow into a smaller subensemble of emitters.

In case that the energy transfer takes place, one can expect that the ensemble emission spectrum will be reduced on the high-energy side, and part of this intensity loss will reappear at a lower energy, since transfer only occurs from smaller to larger NCs. Such a spectral deformation can be induced by reabsorption of higher energy photons or by direct (photonless) ET between adjacent NCs; in either case, the measured PL band will be red-shifted and will not have the usual Gaussian distribution of photon energies (resulting from the Gaussian distribution of NC sizes). Since the optical characteristics of the investigated samples are known, the PL spectrum can be easily corrected for reabsorption using the Lambert–Beer law.
where \( \frac{I_0(\lambda)}{I(\lambda)} = OD \)

Figure 2. (a) Normalized PL spectrum for sample A as-prepared (black) and sufficiently diluted (gray), corrected for reabsorption. Plotted in the same graph is the uncorrected spectrum of the as-prepared sample to demonstrate the effect of reabsorption on the emission spectrum. The solid line indicates where the time-resolved signal is detected. (b) PL decay detected at 2.38 eV for the respective samples. (c, d) Normalized time-resolved PL signal recorded at different detection energies for samples A and B, respectively.

![Figure 2](image1.png)

Figure 3. PL spectra (corrected for reabsorption) of sample A as-prepared (a, black) and diluted (b, gray). The spectra are fitted using a number of Gaussian subcomponents (dotted lines) with the same peak energy for both samples (indicated by the colored arrows). (c) For each component the increase and decrease of the area under the curve are given. For the chosen components, we find a maximum increase of 50% at 2.4 eV and a decrease of 95% at 2.45 eV.

![Figure 3](image2.png)
are corrected for a possible remaining reabsorption. Figure 4a shows the PL spectra of the samples A and B and their different mixtures. We clearly observe a shift of the PL spectrum, with the maximum changing continuously from that of the small NCs (sample A) to that of the larger ones (sample B) while an increasing fraction of small NCs is gradually substituted by the large ones. Furthermore, for the 1:1 and 1:4 mixing ratios (blue and green spectra), a shoulder appears, being consistent with the two different sizes present in the sample. Figure 4b shows the time-resolved PL signal for samples A and B and the 1:1 mix (brown, orange, blue), detected at 2.39 eV. Included in the same graph is the simulated decay trace of the 1:1 mixed sample. This is obtained from simply summing the two experimentally obtained PL decay signals of samples A and B and subsequent dividing by two. It can be clearly seen that the simulated and the experimentally obtained PL decays are not identical. This indicates that an additional transfer processes is enabled upon mixing.

The ET can be further analyzed by comparing the experimentally measured PL spectra of the mixed samples and their simulated spectra. The latter are obtained, similarly as shown in Figure 4b, from adding the measured PL spectra of samples A and B (a) corrected for reabsorption (Figure S1); PL lifetimes at different detection energies for sample A (Figure S2); comparison of the normalized PL spectra measured and simulated (Figure S3); fitting of the normalized PL spectra of sample A corrected for reabsorption (Figure S4); TEM image of NCs aggregation (Figure S5); normalized PL spectra for the different mixed samples (Figure S6) (PDF).

4. CONCLUSIONS

We have established the presence of effective ET between inorganic perovskite CsPbBr3 NCs in colloidal state, driven by concentration and energy gradients. This opens new insights for application of perovskite NCs where the ET can be engineered toward a specific goal.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.jpcc.6b04768. Absorption spectra of all considered samples with and without correction for the solvent absorption and the corresponding PL spectra (Figure S1); PL lifetimes at different detection energies for sample A (Figure S2); comparison of the normalized PL spectra measured and simulated (Figure S3); fitting of the normalized PL spectra of sample A corrected for reabsorption (Figure S4); TEM image of NCs aggregation (Figure S5); normalized PL spectra for the different mixed samples (Figure S6) (PDF).

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Author Contributions
C.d.W. and L.G. contributed equally. C.d.W., L.G., and T.G. conceived the project and designed the experiments; L.G. and G.N. prepared the samples; C.d.W. performed the spectroscopy measurements; G.N. and M.V.K. performed the TEM measurements; C.d.W. analyzed the data; C.d.W., L.G., and T.G. interpreted the data and cowrote the manuscript; H.Z. and W.J.B. facilitated the ultrafast time-resolved experiments; H.Z., W.J.B., G.N., and M.V.K. edited the manuscript. The manuscript was written through contributions of all authors. All authors have given approval to the final version of the manuscript.

Notes
The authors declare no competing financial interest.

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