Asynchronous Photoexcited Electronic and Structural Relaxation in Lead-Free Perovskites

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ABSTRACT: Vacancy-ordered lead-free perovskites with more-stable crystalline structures have been intensively explored as the alternatives for resolving the toxic and long-term stability issues of lead halide perovskites (LHPs). The dispersive energy bands produced by the closely packed halide octahedral sublattice in these perovskites are meanwhile anticipated to facility the mobility of charge carriers. However, these perovskites suffer from unexpectedly poor charge carrier transport. To tackle this issue, we have employed the ultrafast, elemental-specific X-ray transient absorption (XTA) spectroscopy to directly probe the photoexcited electronic and structural dynamics of a prototypical vacancy-ordered lead-free perovskite (Cs3Bi2Br9). We have discovered that the photogenerated holes quickly self-trapped at Br centers, simultaneously distorting the local lattice structure, likely forming small polarons in the configuration of Vk center (Br2− dimer). More significantly, we have found a surprisingly long-lived, structural distorted state with a lifetime of ∼59 μs, which is ∼3 orders of magnitude slower than that of the charge carrier recombination. Such long-lived structural distortion may produce a transient “background” under continuous light illumination, influencing the charge carrier transport along the lattice framework.

INTRODUCTION

Lead halide perovskite (LHP)-based solar cells have received immense attention in recent years, because of their low cost and superior power conversion efficiency.1−4 However, the commercialization of LHP solar cells is currently limited by the potential environmental and public health concerns, which result from the toxicity of water-soluble, unstable lead salts under ambient conditions.5,6 The vacancy-ordered lead-free perovskites, such as Sn- or Te-based double perovskites,7−9 and Bi- or Sb-based two-dimensional (2D) layered perovskites, as well as their zero-dimensional (0D) ones,9−12 have been explored as low/nontoxic replacements for LHPs, because of their stabilized crystalline lattice structures. Although the octahedral connectivity in these perovskites is reduced, the closely packed halide octahedral sublattice is still anticipated to provide dispersive energy bands for good charge carrier mobility.13 However, the power conversion efficiency of such perovskite-based devices is far below expectations.9,12,14

Photoexcitation of LHPs with energy above the bandgap creates the charge carriers, namely, electrons (e−) and holes (h+). The photogenerated charge carriers might be trapped,
accompanied by lattice distortion due to the strong carrier–phonon interaction.\(^{15-20}\) This process is known as polaron formation, and it has been recently used to rationalize the intrinsic origin of the success of LHPs in photovoltaic applications. Nonetheless, the conclusion of polaron formation is mainly derived or speculated through indirect experiments or calculations.\(^{15-20}\) Hence, direct experimental observation of the electronic and structural dynamics correlated with polaron formation and relaxation is crucial in uncovering the fundamentally photophysical mechanisms of perovskite materials. Recently, we have directly observed the photoinduced electron polaron formation in an LHP.\(^{21}\) However, knowledge of polaron formation in lead-free perovskites is largely missing, despite of its great importance.

Herein, using the ultrafast, elemental-specific X-ray transient absorption (XTA) spectroscopy (see the description of the technique given in the Supporting Information and the setup schematic shown in Figure S1 in the Supporting Information), we directly visualized the photoinduced electronic and structural dynamics of a prototypical vacancy-ordered, lead-free perovskite: Cs\(_3\)Bi\(_2\)Br\(_9\) (space group P\(_{3}\)\(\overline{1}\), \(a = 7.972 \ \text{Å} \) and \(c = 9.867 \ \text{Å}\), in the form of \(\sim 3.8 \ \text{nm}\) nanocrystals (NCs) (see Figures S2 and S3 in the Supporting Information), which were prepared by a modified one-step reaction method (see details in the Supporting Information).\(^{22}\) The NCs exhibit a strong exciton peak at 2.84 eV in their UV-vis absorption spectrum, because of their own natural quantum wells caused by their vacancy-ordered 2D-layered structures (see Figures S2b and S3b in the Supporting Information) and each NC is composed of \(\sim 54\) unit cells (see the calculations in the Supporting Information). Our experimental results evidence the photoinduced small polaron formation in Cs\(_3\)Bi\(_2\)Br\(_9\) NCs, in which the photoexcited hole is fast self-trapped (<10 ps) at the Br ions, distorting the Br local lattice structure. Surprisingly, we have observed an ultra-long-lived structural distorted intermediate state (\(\sim 59\) ps), which is 3 orders of magnitude slower than the recombination (\(\sim 20\) ns) between the electrons and self-trapped holes. Our findings here represent a step forward in uncovering fundamental mechanistic details on the electronic and structural response of the photoinduced polaron state in perovskite materials.

## RESULTS AND DISCUSSION

In consideration of the \(\sim 120\) ps time resolution of the XTA spectroscopic technique here, femtosecond optical transient absorption (fs-OTA) spectroscopy (detailed in the Supporting Information) was first performed to measure the early time relaxation dynamics of photoexcited charge carriers (e\(^-\) and h\(^+\)), using 120 fs laser pulses of 3.1 eV as the pump and broadband 120 fs visible pulses as the probe. According to the electronic density of states (EDOS) (Figure 1a) projected from the band structure (Figure S4 in the Supporting Information) of bulk Cs\(_3\)Bi\(_2\)Br\(_9\) perovskite calculated by density functional theory (DFT), the laser excitons excite the electrons in the valence band (VB) that is primarily composed of Br 4p orbitals to the conduction band (CB) majorly contributed by Bi 6p orbitals hybridized with a small amount of Br 4p orbitals (Bi 6p/Br 4p hybrid). Figure 1b shows the normalized charge carrier kinetics by monitoring the photoinduced absorption (XTA) kinetics of bulk Cs\(_3\)Bi\(_2\)Br\(_9\) perovskite calculated by DFT (Figure S4 in the Supporting Information), under the laser pump flux \(J_p\) from 1.9 \times 10^{15} \ \text{photons/cm}^2 ((\langle N_d \rangle = 0.02)) \text{ to } 5.6 \times 10^{15} \ \text{photons/cm}^2 ((\langle N_d \rangle = 6.7)), \text{ where } \langle N_d \rangle \text{ is the averaged number of photons per nanoparticle (see details in the Supporting Information). The decay kinetics here does not vary with the laser pump flux, implying an insignificant Auger recombination effect, which can be further confirmed by the linear power-dependent amplitudes of exciton state photobleaching at time delays of 1 ps, 90 ps, and 1 ns (see Figure S5b in the Supporting Information). The fitting of these decay curves with a multipexponential model reveals three lifetime components of 0.5 ± 0.1 ps (44%), 9.3 ± 0.7 ps (32%), and 628 ± 37 ps (24%) for charge carrier relaxation dynamics, assignments of which would be discussed with XTA results later.

While OTA spectroscopy provides valuable information on the charge carrier dynamics, it cannot ambiguously distinguish the contribution from different types of charge carriers (e\(^-\) and h\(^+\)) or from different atomic centers. Nor can it track the excited state that does not possess transition strength over the laser spectrum range, which is referred as the optically dark state. The intrinsic, element-specific, oxidation state and local structure sensitive characteristics of XTA technique enable it as an ideal tool to interrogate how charge carriers flow inside the perovskite, as well as distort the local lattice structure. The XTA measurements were performed using ~1.6 ps laser pulses of 3.1 eV as the pump and 120 ps X-ray pulse train from a synchrotron source as the probe (see Figure S1). Figure 2a shows Br K-edge X-ray absorption (XA) spectra of NCs in the ground state (GS) (\(\mu(E)\), black curve) and at the time delay (\(\Delta t\)) of 90 ps (red curve) after laser excitation. The Br K-edge absorption measures the transition from the Br 1s orbital to
upper unoccupied orbitals and the continuum with p-characteristics.23,24 Thus, we can attribute the shoulder peak at the left side of the main edge absorption peak (13.4844 keV), centered at ~13.4802 keV, to the transition from the Br 1s orbital to the bottom of the empty conduction band, namely, the Bi 6p (major)/Br 4p (minor) hybridized state (see Figure 2b(1)). This assignment has been further confirmed by ORCA calculation (see Figure S6 in the Supporting Information). The main edge absorption transition that peaked at 13.4844 keV is due to the Br 1s to p continuum transition (called the X-ray absorption white line). The peak at ~13.499 keV in the GS XA spectrum (Figure 2a, black curve) is caused by the scattering of X-ray created photoelectrons by the neighboring atoms around the Br atoms, directly reflecting the local geometric structure around Br sites.23,24

Similar XTA measurements were conducted at the Bi L3-edge (Bi 2p3/2 orbital to upper unoccupied orbitals and a continuum with d-characteristics) to detect the photoexcited electrons. The results showed no detectable difference absorption between with and without laser excitation within the experimental resolution even by doubling the laser photon flux as used in Br K-edge measurements (see Figure S7 in the Supporting Information). Further increasing the laser power leads to the fast photodegradation of NCs. One possible explanation for this is that most of the photogenerated electrons are highly deviated from Bi cations by the strong coulomb interaction of the hole self-trapped at Br anions, which is also indicated by the prominent exciton peak in the UV-vis spectrum (see Figure S2d in the Supporting Information). This finding agrees with the observation of electron delocalization from Pb site that is obtained by measuring the Pb L3-edge absorption of CsPbBr3 NCs.25

To better illustrate the XA change before and after laser excitation, the XTA spectrum obtained by subtracting $\mu(E)_{\text{GS}}$ from $\mu(E)_{\text{laser-on}}$ ($\Delta t = 90$ ps) was also shown in Figure 2a (purple curve). The main features in the XTA spectrum are indicated by labels "(a)"−"(f)". The sharp positive feature "(a)" before the shoulder peak (13.4802 keV) in the GS XA spectrum indicates that the photoexcitation induces an extra Br 1s-to-p transition (13.4775 keV). As laser photons pump the electrons from the VB to the CB, the Br 4p holes are created in the VB, resulting in an extra XA transition of Br 1s electrons to 4p holes in the VB (Figure 2b(2)), which is shown as feature "(a)" in the XTA spectrum. Such a transition does not exist in the GS XA spectrum, because the VB is fully occupied by the electrons in the GS (Figure 2b(1)). Therefore, feature "(a)" directly reflects the photocreated hole density at Br atom centers. Since features "(e)" and "(f)" correspond to the
scattering peak in the GS spectrum, they can be mainly associated with the photoinduced local structural change around Br atoms. Features "(b)", "(c)", and "(d)" first show the reduction and then the increase of Br 1s to the CB Bi 6p/Br 4p and p continuum transitions, indicating that both transitions shift to higher energies. The photoexcitation reduces the electron density at Br centers so that it lowers the electronic screening effect, resulting in the increase of absorption edge energies. The edge energies are sensitive to both the oxidation state and the local structure, which are often coupled together, showing a combination effect of both in the near-edge region.26−28 Therefore, it is difficult to separate the charge and structure effects on features "(b)"−"(d)".

Figure 3a shows a series of Br K-edge XTA spectra collected at early Δt, ranging from 90 ps to 1.84 μs. Feature "(a)", which reflects photoexcited holes trapped at Br centers, quickly decreases and almost disappears at Δt = 100 ns. By contrast, features "(e)" and "(f)" that are mainly associated with the local structural change clearly exist at Δt = 1.84 μs and are still present at Δt = 35 μs (Figure 3b). This implies that the small local structural distortion exists even after Br 4p holes in the valence band are recombined by the electrons. The shape of the XTA spectra after 100 ns shows no detectable changes (see Figure S7), suggesting only one intermediate state over the μs-scale delay range. In order to quantitatively extract the time scales for relaxation dynamics of the self-trapped holes and for the recovery dynamics of the local structural distortion around Br atoms, the XTA kinetics were measured at two peaks: "(a)" and "(f)", which are fingerprints for hole self-trapping and structural distortion, respectively. These two kinetics (Figure 3c) are very similar in the first 5 ns but grow apart later. The fitting of kinetics probed at the peak "(a)" by the multiple-exponential function convoluted with Gaussian instrument response function (IRF) of ~120 ps (fwhm) reveal three lifetime components: 628 ± 37 ps (15%), 11.4 ± 1.1 ns (70%), and 81.0 ± 4.2 ns (15%), giving an amplitude-averaged lifetime of 20.2 ± 1.0 ns. The lifetime component of ~628 ps for self-trapped hole relaxation has also been captured by fs-OTA, which indicates that hole tapping must happen prior to this, in the hot carrier thermalization processes of ~0.5 ps or ~9.3 ps measured in fs-OTA (Figure 1b) or earlier. In other words, the hole is fast localized at the Br atom in the time scale of <10 ps. Furthermore, the ~628 ps lifetime component can be attributed to the radiative recombination between the electron and the localized hole, according to our previous OTA and PL results.22 As for the other two lifetime components of ~11.4 and 81 ns, they might be assigned to be the nonradiative recombination between the electron and self-trapped hole by emitting multiple phonons via two different pathways, in which the self-trapped hole is directly recombined by the electron or it is first detrapped and then recombined by the electron. Besides sharing those lifetime components (~628 ps (18%),...
namely, the V\textsubscript{k} center) between two nearest-neighbor halideScenario-1), or two neighboring [BiBr\textsubscript{6}] units (Scenario-2) in the unit cell (see Figure S3 in the Supporting Information). The distance between the two nearest Br ions is \( \sim 3.9 \) Å in the ground state. As for the Br\textsuperscript{2−} dimer (V\textsubscript{k} center) formation, the distance of \( \sim 3.1 \)−3.3 Å between two Br atoms in Scenario-2 was found to best simulate experimental XTA spectrum at 90 ps. The first positive peak (denoted by an asterisk, *) for the electronic change due to the hole self-trapping in the experimental XTA spectrum cannot be reproduced from the FEFF9 simulations, because of the deficiency of FEFF9.

\[ \Delta \mu = \mu_{\text{exp}} - \mu_{\text{calc}} \]

\[ \Delta \mu = 90 \text{ ps} \]

Figure 6. Comparison between experimental Br K-edge XTA spectrum of Cs\textsubscript{3}Bi\textsubscript{2}Br\textsubscript{9} perovskite at \( \Delta t = 90 \) ps and FEFF9 calculated ones in two scenarios, where the Br\textsuperscript{2−} dimer (V\textsubscript{k} center) are formed by moving two adjacent Br atoms from a same [BiBr\textsubscript{6}] unit (Scenario-1) or two neighboring [BiBr\textsubscript{6}] units (Scenario-2) in the unit cell (see Figure S3 in the Supporting Information). The distance between the two nearest Br ions is \( \sim 3.9 \) Å in the ground state. As for the Br\textsuperscript{2−} dimer (V\textsubscript{k} center) formation, the distance of \( \sim 3.1 \)−3.3 Å between two Br atoms in Scenario-2 was found to best simulate experimental XTA spectrum at 90 ps. The first positive peak (denoted by an asterisk, *) for the electronic change due to the hole self-trapping in the experimental XTA spectrum cannot be reproduced from the FEFF9 simulations, because of the deficiency of FEFF9.

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\[ \Delta \mu = 90 \text{ ps} \]
the Boltzmann constant, and T the temperature. To estimate $\Delta_G$, we calculated the phonon density of states (PDOS) of the Br atom versus its vibration frequency by projecting the phonon band structure of Cs$_3$Bi$_2$Br$_9$ bulk (see Figure S9 in the Supporting Information). As shown in Figure 5c, the Br atom mainly vibrates between the ranges of 0.5–2.8 THz and 4.0–5.7 THz, giving an amplitude-average frequency of 2.7 THz. Using $\tau^{-1} = 16.9$ kHz ($\sim$59 $\mu$s$^{-1}$) and $\tau_0^{-1} = 2.7$ THz, the average $\Delta_G$ is estimated to be $-0.485$ eV at room temperature. These Br-dominated modes are localized eigenstates (Figure S9), among which the optically active modes, such as rocking and rotating modes, could facilitate the formation of Br$_2$ dimer ($V_l$ center) via strong coupling with charge carriers.

The structural dynamics of NCs may be different from that of the bulk material, because of the high surface-area-to-volume ratio in NCs. However, considering that the exciton behavior of Cs$_3$Bi$_2$Br$_9$ as a layered form of the vacancy-ordered lead-free perovskites is dominated by its own 2D natural quantum wells, we expected that the structure and charge carrier dynamics findings here for Cs$_3$Bi$_2$Br$_9$ NCs may also be applied to their bulk counterparts.

#### CONCLUSION

This work demonstrates the great potential of using XTA to directly visualize charge and structure evolution of photoexcited perovskite materials, which is a critical step in understanding the fundamental mechanism that governs their performance. We have observed the photoinduced small polaron formation in lead-free perovskites and have discovered that structural and electronic dynamics of small polarons in perovskites are not necessarily synchronized and could differ in lifetimes by up to several orders of magnitude. The ultra-long-lived structural distortion may lead to an equilibrium long-range disorder of the lattices under continuous light irradiation as a transient “background state”, altering charge carrier transport characteristics. The results from this study can further supply one possible structural interpretation for the current density-voltage ($J$–$V$) hysteresis and photodegradation/fast-healing of perovskite solar cells, which are believed to be correlated with the slow structural relaxation to the initial state.

#### ASSOCIATED CONTENT

* Supporting Information
  The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/jacs.9b04557.

Sample preparation and characterizations, theoretical computation methods and data including DFT for electronic and phonon structures, pump flux and average excition number, FEFF-simulated XTA spectra, photothermal effect and ORCA for near-edge electronic transition in XA (PDF)

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**Notes**

The authors declare no competing financial interest.

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