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Introduction 1.

Organic-inorganic hybrid compounds with perovskite structures have been extensively investigated in recent years.¹ An interesting class of compounds with perovskite structures is the diammonium series, which forms layered perovskite halogen salts, as well as the monoammonium series, which has the formula $[C_nH_{2n+1}NH_3]_2MX_4$ (*n* = 2, 3, ...; M = Mn, Co, Cu, Zn, Cd, X = Cl, Br).²⁻¹⁴ The diammonium series $[NH_3(CH_2)_n NH_3]$ MX₄ has been studied because of its H-bonds and excellent stability.¹¹⁻¹⁶ [NH₃(CH₂)_nNH₃]MX₄ compounds with zero- and two-dimensional hybrid perovskite structures have attracted considerable attention in recent years. For M = Mn, Cu, and Cd, the structure consists of a corner-shared octahedron $(MX_6)^{2-1}$ positioned between the organic layers and is two-dimensional. For M = Co and Zn, isolated tetrahedral structures form inorganic $(MX_4)^{2-}$ layers between layers of organic cations and are zero-dimensional.¹⁷⁻²² $[NH_3(CH_2)_nNH_3]ZnCl_4$ (M = Zn and X = Cl) compounds crystallize in a perovskite-like structure, in which the link between adjacent ZnCl₄ octahedral planes is formed by the alkylene chains with NH₃ groups at both ends.

Effect of methylene chain length of perovskite-type layered $[NH_3(CH_2)_nNH_3]ZnCl_4$ (n = 2, 3, and 4) crystals on thermodynamic properties, structural geometry, and molecular dynamics[†]

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The structure of organic-inorganic perovskite [NH₃(CH₂)₄NH₃]ZnCl₄ was determined; the lattice constants with monoclinic structure were determined to be a = 7.2527 Å, b = 8.1101 Å, c = 10.3842 Å, and $\beta =$ 80.3436°. The crystal was almost thermally stable up to approximately 560 K. The endothermic peaks at 481 K and 506 K were assigned to the phase transition of the material. In addition, the structural characteristics and molecular dynamics of the cation were studied via magic angle spinning nuclear magnetic resonance experiments. Based on the results, the effects of the length of the CH₂ group in the cation of the $[NH_3(CH_2)_nNH_3]ZnCl_4$ (n = 2, 3, and 4) crystals were considered. Regardless of whether n was even or odd, the differences in the thermal and physical properties were minimal. Moreover, a difference in molecular motion relative to the length of the cation was observed only at high temperatures. These results provide useful information about the thermal stability and molecular dynamics of [NH₃(CH₂)_nNH₃]ZnCl₄ crystals and are expected to facilitate potential applications of such compounds in supercapacitors, batteries, and fuel cells.

> The $[NH_3(CH_2)_nNH_3]$ organic chains extend along the longest caxis, are located between the inorganic layers, and are connected to these layers through N-H…Cl hydrogen bonding.23,24 Hence, the distance between two neighboring inorganic layers depends on the length of the organic chain. The Zn atom is surrounded by four Cl atoms to form the ZnCl₄ tetrahedra. These compounds are of considerable interest because of the diversity of their crystal structures, which govern their thermodynamic properties and structural dynamics. Materials such as perovskites are expected to be used for a variety of applications, including photovoltaics, photocatalysis, batteries,25 energy storage, and micro-and nanoelectronics.^{26,27} The [NH₃(- CH_2 _nNH₃ZnCl₄ studied here is expected to be used in various applications as it can improve relatively weak thermal stability and eco-friendly.

> The synthesis and characterization of [NH₃(CH₂)_nNH₃]ZnCl₄ crystals with n = 2 and 3 have been reported based on X-ray diffraction.^{23,24} Recently, the physicochemical properties and structural dynamics of crystals with n = 2 and 3 were investigated in terms of the changes in chemical shifts and nuclear magnetic resonance (NMR) spin-lattice relaxation times with temperature.28,29 Although these compounds have several applications, the physical properties of [NH₃(CH₂)₄NH₃]ZnCl₄ crystals have not been discussed in detail.

> Physicochemical properties are essential for understanding the structural dynamics of the [NH₃(CH₂)₄NH₃] cation in the [NH₃(CH₂)₄NH₃]ZnCl₄ crystal. Solid state NMR has proven

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a useful method for study of local structure and mobility.³⁰ By studying the spin–lattice relaxation time $T_{1\rho}$ of the each nuclei in different environments, it is possible to obtain information about the dynamical processes occurring in different parts.

The aim of this study was to investigate the thermodynamic properties and molecular dynamics of 1,4-butanediyldiammonium tetrachlorozincate ($[NH_3(CH_2)_4NH_3]ZnCl_4$) crystals with n = 4. The crystal structures, phase-transition temperatures, and thermodynamic properties of the crystals were investigated using X-ray diffraction, thermogravimetric analysis (TGA), and differential thermal analysis (DTA). In addition, the chemical shifts and spin-lattice relaxation time $T_{1\rho}$ were analyzed using ¹H magic angle spinning (MAS) NMR, ¹³C MAS NMR, and static ¹⁴N NMR, according to the temperature change, to determine the characteristics of the [NH₃(CH₂)₄NH₃] cation. The effects of the length of the CH_2 group in the cation of the $[NH_3(CH_2)_4NH_3]$ ZnCl₄ crystal were considered, along with previously reported effects in [NH₃(CH₂)₂NH₃]ZnCl₄ and [NH₃(CH₂)₃NH₃]ZnCl₄. The results provide insights into the structural dynamics of [NH₃(- CH_2 _nNH₃]ZnCl₄ crystals (n = 2, 3, and 4) based on the methylene chain length and are expected to facilitate potential applications in the future.

2. Experimental method

An aqueous solution containing $NH_2(CH_2)_4NH_2 \cdot 2HCl$ and $ZnCl_2$ was slowly evaporated at a constant temperature of 300 K to produce single crystals of $[NH_3(CH_2)_4NH_3]ZnCl_4$. The transparent crystals were produced within 3–4 weeks and exhibited some good quality shapes. The structure of the crystal at 298 K was analyzed using single-crystal X-ray diffraction at the Seoul Western Center of the Korea Basic Science Institute (KBSI). The crystals were mounted on a Bruker D8 Venture equipped with a 1 μ s micro-focus sealed tube with Mo-K α radiation and a PHOTON III M14 detector.

TGA and DTA experiments were performed on a thermogravimetric analyzer (TA Instrument) at a heating rate of 10 K min⁻¹ between from 300 to 873 K under N₂ gas. In addition, optical observations were performed using an optical polarizing microscope in the temperature range of 300–680 K, with a Linkam THM-600 heating stage.

NMR spectra of $[NH_3(CH_2)_4NH_3]ZnCl_4$ crystals were obtained using a Bruker 400 MHz Avance II + solid-state NMR spectrometer at the Seoul Western Center, KBSI. The Larmor frequencies for the ¹H MAS NMR and ¹³C MAS NMR experiments were 400.13 and 100.61 MHz, respectively. The MAS rate to minimize the spinning sideband was 10 kHz, and tetramethylsilane (TMS) was used as the standard for NMR chemical shifts. The $T_{1\rho}$ values were obtained using a 90° – τ pulse followed by a spin-lock pulse with a duration of τ ; the width of the 90° pulse for ¹H and ¹³C was 3.5–3.9 µs. In addition, static ¹⁴N NMR spectra were measured under a Larmor frequency of 28.90 MHz. The ¹⁴N NMR experiments were performed using one pulse with a 90° pulse width of 6 µs. The chemical shift measurements were referenced using NH₄NO₃ as the standard sample. The temperature was changed by adjusting the heater current and nitrogen gas flow, and it was maintained within $\pm 0.5~\text{K}.$

3. Results and discussion

3.1 Crystal structure

The X-ray powder diffraction pattern of the $[NH_3(CH_2)_4NH_3]$ ZnCl₄ is presented in ESI 1.† Single-crystal X-ray diffraction experiments were conducted on $[NH_3(CH_2)_4NH_3]$ ZnCl₄ at 298 K, and the structure was determined to be triclinic with the *P*1 space group. The lattice constants were determined to be a =7.2839 ± 0.0001 Å, $b = 8.1354 \pm 0.0001$ Å, $c = 10.4592 \pm 0.0002$ Å, and $\alpha = 77.6527 \pm 0.0005^{\circ}$, $\beta = 80.3358 \pm 0.0004^{\circ}$, $\gamma =$ 82.8355 ± 0.0005° (ESI 2†). In addition, the structures, lattice constants, and space groups of $[NH_3(CH_2)_nNH_3]$ ZnCl₄ (n = 2, 3, and 4) were shown in ESI 3.† Among the three single crystals, the previously reported crystal structure for $[NH_3(CH_2)_3NH_3]$ ZnCl₄ with n = 3 is shown in Fig. 1 (CCDC number: 1227730).²³

3.2 Thermal properties

The TGA and DTA experiments were conducted at a heating rate of 10 K min⁻¹; the results shown in Fig. 2. The TGA curve shows that the crystal is almost stable up to approximately 560 K. The endothermic peaks at 481 K ($=T_{C1}$) and 506 K ($=T_{C2}$) on the DTA curve were assigned to the phase transition of the material. The molecular weight loss near 560 K marks the onset of partial thermal decomposition (T_d) . $[NH_3(CH_2)_4NH_3]ZnCl_4$ undergoes a loss in molecular weight with increasing temperature. The amount remaining as solid residue was calculated from the molecular weights. Additionally, weight losses of 12% and 25% occurred at temperatures of 604 K and 622 K, respectively, due to the loss of the HCl and 2HCl moieties. Near 900 K, 95% of the total weight of the crystal was lost. To understand the TGA results, the change in the appearance of the crystals with the increase in temperature was confirmed based on optical polarizing microscopy. Even when the temperature rises from 300 K to 490 K, the single crystal is transparent and colorless, but when the temperature reaches 520 K, it starts to melt slightly, and a considerable amount of it melts at 543 K (Fig. 3).



Fig. 1 Structure of $[NH_3(CH_2)_3NH_3]ZnCl_4$ crystal at 300 K (CCDC number: 1227730).



Fig. 2 Thermogravimetric analysis (TGA) and differential thermal analysis (DTA) curves of $[\rm NH_3(CH_2)_4\rm NH_3]\rm ZnCl_4.$



Fig. 3 Changes in crystal by optical polarizing microscopy at (a) 300 K, (b) 490 K, (c) 520 K, and (d) 543 K for $[NH_3(CH_2)_4NH_3]ZnCl_4$.

3.3 The ¹H MAS NMR

The ¹H MAS NMR spectra of the $[NH_3(CH_2)_4NH_3]ZnCl_4$ crystals were recorded according to the temperature change, and the results of the ¹H chemical shifts are shown in Fig. 4; the spinning sidebands are marked with pluses. The ¹H chemical shift at 300 K was recorded at 6.95 ppm. Below 380 K, only one resonance line is observed, but the NMR spectrum has an asymmetric shape; the left (a) and right (b) sides at the fullwidth-at-half-maximum (FWHM) are not equal. The asymmetric shape of the resonance line corresponds to the overlapping lines of ¹H in NH₃ and CH₂. The ¹H NMR chemical shifts were observed to be temperature-independent, which implies that the environment around ¹H does not change with temperature. However, above 380 K, the ¹H signal was split into four sharp lines (2, 3, 4, and 5), matching the number of ¹H signals in different environments. The number 1 denotes ¹H in NH₃, and the remaining four signals represent ¹H in CH₂, arbitrarily indicated by the numbers 2, 3, 4 and 5. The temperature-sensitive above 380 K, indicating that the structure of the environment surrounding ¹H in the [NH₃(CH₂)₄NH₃] cation changes.

The ¹H MAS NMR spectra were measured with several delay times at each given temperature. The plot of spectral intensities against the delay times is described by a single exponential function. The decay rate of the proton magnetization is characterized by the spin–lattice relaxation time $T_{1\rho}$:^{30,31}

$$P(\tau)/P(0) = \exp(-\tau/T_{1\rho}), \qquad (1)$$

Here, $P(\tau)$ and P(0) are the signal intensities at times τ and $\tau = 0$, respectively. The $T_{1\rho}$ is an important experimental quantify for the study of the local dynamics. From the slope of the logarithm of intensity–delay time plots, the ¹H $T_{1\rho}$ values were determined at several temperatures. An example of magnetization decay at 300 K is represented by the intensity of the signal against the delay time from 0.2 to 150 ms, as shown in Fig. 5. The intensities indicated by arrow *vs.* delay time are described by a single exponential function from the slope of their recovery traces. Moreover, the ¹H $T_{1\rho}$ values in $[NH_3(CH_2)_4NH_3]ZnCl_4$ were obtained as a function of inverse temperature, as shown in Fig. 6. As the temperature rises, $T_{1\rho}$ gradually increases without anomalous changes till 350 K, after which it decreases slightly. The E_a values were calculated from $T_{1\rho}\alpha \exp(\pm E_a/k_BT)$, where E_a is the activation energy for molecular motion, k_B is the



Fig. 4 MAS 1 H NMR chemical shifts of [NH₃(CH₂)₄NH₃]ZnCl₄ as a function of temperature.



Fig. 5 Magnetization recovery curves of the MAS 1 H NMR spectrum in [NH₃(CH₂)₄NH₃]ZnCl₄ at 300 K, for delay times of 0.2–160 ms.

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Fig. 6 ¹H NMR spin-lattice relaxation times $T_{1\rho}$ of $[NH_3(CH_2)_nNH_3]$ $ZnCl_4$ (n = 2, 3, and 4) as a function of inverse temperature. The solid lines represent activation energy (inset: correlation times for $T_{1\rho}$ as a function of inverse temperature for n = 2).

Boltzmann constant, and T is the temperature. And, E_a values were determined to be 5.56 \pm 0.43 kJ mol⁻¹ at low temperatures and 2.30 \pm 0.94 kJ mol⁻¹ at high temperatures, as indicated by the solid lines in Fig. 6.

To understand the effect of the methylene chain length, we compared our results with previously reported findings regarding [NH₃(CH₂)₂NH₃]ZnCl₄ and [NH₃(CH₂)₃NH₃]ZnCl₄ (with n = 2 and 3).^{28,29} The ¹H $T_{1\rho}$ results for the three compounds (n = 2, 3, and 4) are shown in Fig. 6 as a function of the inverse temperature. In the case of n = 2, as the temperature rises, $T_{1\rho}$ gradually increases and then reaches a maximum value of 570 ms at 270 K, before rapidly decreasing above 300 K. As shown in Fig. 6, $T_{1\rho}$ subsequently reaches its minimum value near 380 K and then tends to increase again.28 This trend between 300 and 430 K indicates the existence of molecular motion. The $T_{1\rho}$ values are related to the correlation time $\tau_{\rm C}$ for molecular motion, as per the Bloembergen-Purcell-Pound (BPP) theory,³² which states that the local field fluctuation is caused by thermal motion. The $\tau_{\rm C}$ -1000/T plot, represented by the olive line on a logarithmic scale, is shown in the inset of Fig. 6. The E_a values for ¹H below and above 300 K were estimated to be 4.91 \pm 0.62 and 78.17 \pm 4.39 kJ mol⁻¹, respectively. On the other hand, for n = 3, $T_{1\rho}$ initially increased and then abruptly decreased when the temperature increased. The $T_{1\rho}$

Table 1 Activation energies E_a determined from spin-lattice relaxation times $T_{1\rho}$ in [NH₃(CH₂)_nNH₃]ZnCl₄ (n = 2, 3, and 4)

| | ¹ H $E_{\rm a}$ (kJ mol ⁻¹) | | ${}^{13}C E_a (kJ mol^{-1})$ | |
|-----------------------|--|---|--|---|
| | Low temp. | High temp. | Low temp. | High temp. |
| n = 2 | 4.91 ± 0.62 | 78.17 ± 4.39 | 2.23 ± 0.45 | 38.88 ± 7.33 |
| n = 3 n = 4 | 3.53 ± 0.02 5.56 ± 0.43 | 31.86 ± 3.82 2 30 ± 0.94 | 1.57 ± 0.21 0.72 ± 0.29 | 1.57 ± 0.21 6 11 ± 0.58 |
| n = 2 $n = 3$ $n = 4$ | Low temp. 4.91 ± 0.62 3.53 ± 0.02 5.56 ± 0.43 | High temp. 78.17 ± 4.39 31.86 ± 3.82 2.30 ± 0.94 | Low temp. 2.23 ± 0.45 1.57 ± 0.21 0.72 ± 0.29 | High tem 38.88 ± 7 1.57 ± 0 6.11 ± 0 |

values of the protons were 100-1000 ms, and these values decreased abruptly at 360 K. The values of E_{2} for ¹H at low and high temperatures were 3.53 ± 0.02 and 31.86 ± 3.82 kJ mol⁻¹, respectively.29

The $E_{\rm a}$ values at low and high temperatures for the three compounds are listed in Table 1. At low temperatures, E_a was almost the same as the length of CH₂ in the cation, whereas at high temperatures, E_a tended to decrease.

3.4 The ¹³C MAS NMR

The ¹³C MAS NMR chemical shifts for CH₂ in the [NH₃(CH₂)₄-NH₃]ZnCl₄ crystal were recorded at several temperatures. One of the MAS ¹³C NMR spectra at 300 K is displayed in Fig. 7, which shows that CH₂-a in the [NH₃(CH₂)₄NH₃] cation is far from NH₃ and that CH₂-b is located near NH₃. The signal for the TMS reference was measured at 38.3 ppm, and this value was set to 0 ppm for the ¹³C chemical shift. The ¹³C NMR chemical shifts of CH₂ were separated into two inequivalent lines for CH₂-a and CH₂-b in [NH₃(CH₂)₄NH₃]ZnCl₄. The CH₂-a and CH₂-b resonance lines themselves were also split into two signals each. This is because the environments of the four carbons in the cation are slightly different. ¹³C chemical shifts were observed at 24.88 and 26.26 ppm for CH2-a and at 40.70 and 41.24 ppm for CH₂-b. In addition, the ¹³C NMR chemical shifts were nearly temperature-independent (ESI 4[†]).

The ¹³C T_{10} relaxations are not affected by spin diffusion, due to the small dipolar coupling, which arises because of the low natural abundance of ¹³C. The intensity changes of the ¹³C NMR spectrum for various delay times in [NH₃(CH₂)₄NH₃]ZnCl₄ were measured, and all the decay curves for CH₂-a and CH₂-b were plotted using a single exponential function. The ${}^{13}C T_{10}$ values shown in Fig. 8 were obtained from the slope of the recovery traces for CH₂-a and CH₂-b, in order to understand the differences in dynamics of ¹³C at different sites. As the temperature increased, the $T_{1\rho}$ values increased at all temperatures. The ¹³C $T_{1\rho}$ values for CH₂-b close to NH₃ are smaller than those for CH₂-a; this indicates that the ¹³C $T_{1\rho}$ values for CH₂-b are more



Fig. 7 MAS ¹³C NMR chemical shifts for CH₂-a and CH₂-b of [NH₃(-CH₂)₄NH₃] ZnCl₄ at 300 K.



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Fig. 8 13 C NMR spin–lattice relaxation times $T_{1\rho}$ of $[NH_3(CH_2)_nNH_3]$ ZnCl₄ (n = 2, 3, and 4) as a function of inverse temperature. The solid lines represent activation energy.

flexible than those for CH₂-a. The $E_{\rm a}$ values represented by the solid lines at low and high temperatures are 0.72 \pm 0.29 and 6.11 \pm 0.58 kJ mol⁻¹, respectively.

To understand the effect of the length n of the CH₂ group in the $[NH_3(CH_2)_nNH_3]$ cation, we compared $[NH_3(CH_2)_2NH_3]$ ZnCl₄, [NH₃(CH₂)₃NH₃]ZnCl₄, and [NH₃(CH₂)₄NH₃]ZnCl₄ with n = 2, 3, and 4. The ¹³C $T_{1\rho}$ results are also shown in Fig. 8 for the three compounds (n = 2, 3, and 4) as a function of the inverse temperature. In the case of n = 2, the ¹³C $T_{1\rho}$ value decreases sharply above 300 K with increasing temperature. The ¹³C $T_{1\rho}$ value at 300 K is 8.35 ms, and at 430 K, it sharply drops to 0.16 ms.28 The activation energies calculated from the slopes of the log $T_{1\rho}$ vs. inverse temperature curves are determined to be 2.23 \pm 0.45 and 38.88 \pm 7.33 kJ mol⁻¹ below and above 300 K, respectively. In addition, the E_a values for CH₂-b below 300 K are almost identical to those of CH2-a within the experimental error range. In the case of n = 3, the ¹³C $T_{1\rho}$ values decreased slightly with increasing temperature but remained between 20 and 60 ms. $E_{\rm a}$ was 1.57 \pm 0.21 kJ mol⁻¹ at all temperatures.

3.5 Static ¹⁴N NMR

Static ¹⁴N NMR investigations of $[NH_3(CH_2)_4NH_3]ZnCl_4$ single crystals were conducted over a temperature range of 180–430 K. The ¹⁴N spectra were obtained using the one-pulse method using static NMR. Two ¹⁴N NMR signals were expected from the quadrupole interactions under a spin number of $I = 1.^{30}$ The ¹⁴N NMR spectrum varied with increasing temperature, as shown in Fig. 9. The measurements were performed by keeping the *c*-axis of the single crystals parallel to the direction of the magnetic field. It was not easy to get ¹⁴N were signals because we were measuring at the low frequency of 28.90 MHz. The four plots in the graph, shown in Fig. 9, were attributed to the two inequivalent NH₃-a and NH₃-b ions. The two inequivalent ¹⁴N resonance lines due to NH₃-a and NH₃-b are related to the two types



Fig. 9 ^{14}N resonance frequency of $[\text{NH}_3(\text{CH}_2)_4\text{NH}_3]\text{ZnCl}_4$ single crystal as a function of temperature.

of ¹³C resonance lines due to CH_2 -a and CH_2 -b. NH_3 -a and NH_3 b were arbitrarily determined for NH_3 . The four resonance lines of the two pairs decreased with increasing temperature to minima near 250 K (red circle) and 370 K (olive square), respectively, and then increased again. Symbols with the same colors indicate the same pairs for ¹⁴N. In addition, the change in the ¹⁴N resonance frequency with temperature is due to structural geometry change, which means a change in the quadrupole coupling constant.³⁴ the chemical shifts of the ¹⁴N signals changed almost continuously without any anomalous changes. The changes in the ¹⁴N chemical shift as a function of temperature were attributed to the variations in the structure of the N–H…Cl hydrogen bonds, indicating changes in the atomic configurations near the ¹⁴N nuclei.

4. Conclusions

Based on information obtained from NMR analyses of the methylene chain length, the structural dynamics of the $[NH_3(-CH_2)_nNH_3]$ cation in $[NH_3(CH_2)_nNH_3]ZnCl_4$ crystals were analyzed in this study. We compared the physical properties of previously reported $[NH_3(CH_2)_2NH_3]ZnCl_4$ and $[NH_3(CH_2)_3NH_3]ZnCl_4$ crystals with those of $[NH_3(CH_2)_4NH_3]ZnCl_4$ examined in this study.

The ¹H chemical shifts for the $NH_3(CH_2)_nNH_3$ cation (n = 2, 3, and 4) were found to be nearly temperature-independent. The two inequivalent CH_2 -a and CH_2 -b were distinguished through ¹³C NMR experiments, and the two inequivalent ¹⁴N were distinguished based on ¹⁴N NMR results.

The behavior of $T_{1\rho}$ for molecular motions with a correlation time $\tau_{\rm C}$ is described in two regimes: fast- and slow-motion regimes. At low temperatures, the ¹H $T_{1\rho}$ values for all three crystals indicated fast motion: $\omega_1 \tau_{\rm C} \ll 1$, $T_{1\rho}^{-1} \alpha \exp(E_{\rm a}/k_{\rm B}T)$. Their values at high temperatures indicated slow motion: $\omega_1 \tau_{\rm C} \gg 1$, $T_{1\rho}^{-1} \alpha \omega_1^{-2} \exp(E_{\rm a}/k_{\rm B}T)$.^{30,33} However, the ¹³C $T_{1\rho}$ values at low and high temperatures for n = 2 and 3 indicated slow This article is licensed under a Creative Commons Attribution-NonCommercial 3.0 Unported Licence.

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motion. In the case of n = 4, ¹³C $T_{1\rho}$ at all temperatures undergoes the fast motion, unlike in the cases of n = 2 and 3. In addition, the ¹H and ¹³C E_a values, measured according to the length of the CH₂ groups in the cation chain, decreased because ¹H and ¹³C became more flexible with increasing length. According to the NMR $T_{1\rho}$ result, as the length of the cation increases, the motion of the methylene chain becomes flexible at high temperatures. This result correlates with the effect of electron-phonon interactions on the luminescence of single crystals of 2D perovskite reported by Gong *et al.*³⁵ The NMR measurements of $T_{1\rho}$, density functional theory simulations and experimental atomic displacements reveal that molecular motion was slowest and most rigid in the brightest emitter.

Solid-state NMR provides information of the material's thermal stability, structural change, and dynamics of the molecular motion depending on the temperature. The molecular motion differed according to the length of the cation and the temperature, and our solid-state NMR study on perovskites can therefore highlight potentials for each perovskite material for specific applications.

Conflicts of interest

There are no conflicts to declare.

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