Role of NH4 ions in successive phase transitions of perovskite type (NH4)2ZnX4 (X = Cl, Br) by 1H MAS NMR and 14N NMR

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1. Introduction

Perovskite A2BX4 type (A = Na, K, Rb; Cs; B = Zn, Co, Cu, Fe, Zn, Cd; X = Cl, Br) crystals have received a great deal of attention because of their nonlinear optical properties, and also because of the significant diversity of their structural phase transitions. The prototype of the crystal structures of this family is that of β-K2SO4, which consists of isolated BX4 tetrahedra and monovalent A+ cations placed in two inequivalent cavities. Ammonium tetrachlorozincate, (NH4)2ZnCl4, and ammonium tetrabromozincate, (NH4)2ZnBr4, belong to the family of crystals of the perovskite ABX4 type and are known to undergo several phase transitions. Although the physical properties of (NH4)2ZnCl4 and (NH4)2ZnBr4 have been studied by several research groups, the structural geometry changes during the phase transitions of the two compounds have not been fully understood. Here, the phase transition temperatures and dynamics of the cations in (NH4)2ZnCl4 and (NH4)2ZnBr4 are important. The potential applications of these materials are strongly affected by the phase transitions and dynamics of the cations.

(NH4)2ZnCl4 undergoes five phase transitions: those between phases I and II at 406 K (= Tc1), phases II and III at 364 K (= Tc2) are well-known, and the successive phase transitions at 319 K (= Tc3), 271 K (= Tc4), and 266 K (= Tc5) have also been reported, the phases involved in these transitions are denoted by VI, V, IV, III, II, and I in order of increasing temperature, as shown in Table 1. The structure of (NH4)2ZnCl4 in the normal phase, phase I (above 406 K), is orthorhombic with a0 = 9.274 Å, b0 = 12.620 Å, and c0 = 7.211 Å, and space group Pnma. Upon cooling, there is a phase transition at 406 K to an incommensurate phase that is stable down to 364 K. The structure in phase III between 364 K and 319 K is orthorhombic with a = a0, b = b0, c = 4c0, and the space group Pn21a. The room temperature phase, phase IV, is antiferroelectric with a pseudo-orthorhombic monoclinic structure and space group Pa. The region between 271 K and 266 K is mixed phase. Below 266 K, the lattice is constant with an orthorhombic structure, where a = a0, b = b0, and c = 3c0.

On the other hand, the successive phase transitions of (NH4)2ZnBr4 have been reported at 216 K (= Tc1), 395 K (= Tc2), and 432 K (= Tc3) as shown in Table 1; the phases involved in these transitions are represented by IV, III, II, and I in order of increasing temperature. The structures of (NH4)2ZnBr4 crystals in phases I, III, and IV are shown in Fig. 1. In phase I (above 432 K), the structure of (NH4)2ZnBr4 is orthorhombic with a0 = 7.649 Å, b0 = 13.353 Å, c0 = 9.727 Å, and space group Pnma. Upon cooling, there is a phase transition at 432 K to an incommensurate phase II that is stable down to 395 K. The structure in phase III, between 395 K and 216 K, is monoclinic with a = a0, b = b0, c = 4c0, β = 90.00(3)°, and space group P21/c. The low-temperature phase IV is orthorhombic with a = a0, b = b0, c = 3c0, and space group P21/c.

The 1H spin-lattice relaxation times of (NH4)2ZnCl4 and (NH4)2ZnBr4 crystals have been obtained in the laboratory frame by Lim et al. and Ramesh et al., respectively. The molecular dynamics and phase transitions of (NH4)2ZnCl4 single crystals were reported previously. There were two crystallographically inequivalent NH4 sites, namely NH4(1) and NH4(2), in the (NH4)2ZnCl4. The 1H spin-lattice relaxation time T1 in the laboratory frame was observed to vary continuously with temperature without jumps or changes. The 1H T1 passes

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1. Introduction

1.1. Phase Transitions

(NH4)2ZnCl4 and (NH4)2ZnBr4 crystals have been studied in each phase of (NH4)2ZnX4 single crystals in the laboratory frame. The phase transition temperatures strongly affect the 14N number of symmetry related nitrogen centers within the unit cell. The 1H MAS NMR and 14N NMR results are discussed to elucidate the roles of NH4 ions during the phase transitions of (NH4)2ZnX4.

1.2. Crystal Structures

The crystal structures of (NH4)2ZnX4 (X = Cl, Br) crystals have received a great deal of attention because of their nonlinear optical properties, and also because of the significant diversity of their structural phase transitions. The structures of (NH4)2ZnX4 (X = Cl, Br) are shown in Fig. 1. The structures of (NH4)2ZnCl4 and (NH4)2ZnBr4 in the normal phase, phase I (above 406 K), are orthorhombic with a0 = 9.274 Å, b0 = 12.620 Å, and c0 = 7.211 Å, and space group Pnma. Upon cooling, there is a phase transition at 406 K to an incommensurate phase that is stable down to 364 K. The structure in phase III between 364 K and 319 K is orthorhombic with a = a0, b = b0, c = 4c0, and the space group Pn21a. The room temperature phase, phase IV, is antiferroelectric with a pseudo-orthorhombic monoclinic structure and space group Pa. The region between 271 K and 266 K is mixed phase. Below 266 K, the lattice is constant with an orthorhombic structure, where a = a0, b = b0, and c = 3c0.

On the other hand, the successive phase transitions of (NH4)2ZnBr4 have been reported at 216 K (= Tc1), 395 K (= Tc2), and 432 K (= Tc3) as shown in Table 1; the phases involved in these transitions are represented by IV, III, II, and I in order of increasing temperature. The structures of (NH4)2ZnBr4 crystals in phases I, III, and IV are shown in Fig. 1. In phase I (above 432 K), the structure of (NH4)2ZnBr4 is orthorhombic with a0 = 7.649 Å, b0 = 13.353 Å, c0 = 9.727 Å, and space group Pnma. Upon cooling, there is a phase transition at 432 K to an incommensurate phase II that is stable down to 395 K. The structure in phase III, between 395 K and 216 K, is monoclinic with a = a0, b = b0, c = 4c0, β = 90.00(3)°, and space group P21/c. The low-temperature phase IV is orthorhombic with a = a0, b = b0, c = 3c0, and space group P21/c.

The 1H spin-lattice relaxation times of (NH4)2ZnCl4 and (NH4)2ZnBr4 crystals have been obtained in the laboratory frame by Lim et al. and Ramesh et al., respectively. The molecular dynamics and phase transitions of (NH4)2ZnCl4 single crystals were reported previously. There were two crystallographically inequivalent NH4 sites, namely NH4(1) and NH4(2), in the (NH4)2ZnCl4. The 1H spin-lattice relaxation time T1 in the laboratory frame was observed to vary continuously with temperature without jumps or changes. The 1H T1 passes
Table 1  Phase transition temperatures, crystal structures, space groups, and lattice constants of (NH₄)₂ZnX₄ (X = Cl, Br)

| (NH₄)₂ZnCl₄ | Tc₁ (≈266 K) | Tc₄ (≈271 K) | Tc₃ (≈319 K) | Tc₂ (≈364 K) | Tc₃ (≈406 K) |
|-------------|--------------|--------------|--------------|--------------|--------------|
| Phase/Structure | VI/Orthorhombic | V/Mixed phase | IV/Moniclinic | III/Orthorhombic | II/Incommensurate |
| Space group | Pna₂₂₁ | a = a₀ | a = a₀ | a = a₀ | a₀ = 9.274 Å |
| Lattice constant | b = b₀ | b = b₀ | b = b₀ | b = b₀ | b₀ = 12.620 Å |
| c = 3c₀ | c = 4c₀ | c = 4c₀ | c = 4c₀ | c = 7.211 Å |
| β = 98.992° | | | | | |
| Reference | 12 and 17 | 14 | 12 | 12, 16 and 17 | 15 | 12 |

| (NH₄)₂ZnBr₄ | Tc₁ (≈216 K) | Tc₂ (≈395 K) | Tc₃ (≈432 K) |
|-------------|--------------|--------------|--------------|
| Phase/Structure | IV/Orthorhombic | III/Moniclinic | II/Incommensurate |
| Space group | P₂₁cn | a = a₀ | a = a₀ |
| Lattice constant | b = b₀ | b = b₀ |
| c = 3c₀ | c = 4c₀ |
| β = 90.0°(3°) | | | |
| Reference | 22 | 20 | 21 and 22 |

through a minimum value near 220 K; the presence of this minimum was attributed to the reorientation of the NH₄ groups. In addition, the ¹⁴N nuclear magnetic resonance (NMR) results in phase I of (NH₄)₂ZnCl₄ were reported for the two inequivalent sites N(1) and N(2): the quadrupole coupling constant, e²Q/h, and asymmetry parameter, η, were e²Q/h = 105.5 kHz and η = 0.96 for N(1), and e²Q/h = 48.2 kHz and η = 0.087 for N(2).²⁷

The NMR method enables the study of a lattice’s local properties, and is particularly useful in those cases that require information on the behavior of individual structural groups. Measurements of T₁, obtained by magic angle spinning (MAS) NMR in the rotating frame are advantageous in that they allow for probing of molecular motion in the kHz range, whereas T₁ values obtained by state NMR in a laboratory frame reflect motion in the MHz range.²⁸

The aim of this paper is to clarify the structural changes associated with the successive phase transitions in (NH₄)₂ZnX₄ (X = Cl, Br). Detailed studies of the molecular motions are necessary in order to explain the mechanisms of the phase transitions of (NH₄)₂ZnX₄. The temperature dependences of the MAS NMR spectra and the spin-lattice relaxation times, T₁, in the rotating frame for the ¹H nuclei in (NH₄)₂ZnX₄ were investigated using a pulsed NMR spectroscopy. In addition, the ¹⁴N NMR spectra in (NH₄)₂ZnX₄ single crystals were obtained by static NMR in the laboratory frame, as a function of temperature. The ¹H MAS NMR and ¹⁴N static NMR results were analyzed to elucidate the roles of NH₄ ions during the phase transitions of (NH₄)₂ZnCl₄ and (NH₄)₂ZnBr₄. The T₁ values by ¹H MAS NMR obtained here and the previously reported T₁ values by ¹H static NMR are compared. In addition, the information regarding the structural geometry of nitrogen environments in NH₄⁺ is discussed as a function of temperature.

2. Experimental method

Single crystals of (NH₄)₂ZnCl₄ and (NH₄)₂ZnBr₄ were obtained by the slow evaporation of aqueous solutions with the appropriate molar ratios of NH₄Cl and ZnCl₂, and NH₄Br and ZnBr₂, respectively, at 298 K.¹²,²⁹,³⁰ These single crystals exhibited hexagonal shapes that were transparent and colorless.

¹H MAS NMR spectra and the spin-lattice relaxation times, T₁, in the rotating frame in (NH₄)₂ZnCl₄ and (NH₄)₂ZnBr₄ were measured in a static magnetic field of 9.4 T and Larmor frequency of ω₀/2π = 400.13 MHz using a Bruker 400 MHz NMR spectroscopy at the Korea Basic Science Institute, Western Seoul Center. The chemical shifts were measured with respect to tetramethylsilane (TMS). Powder samples were placed inside a 4 mm cross-polarization (CP)/MAS probe, and the MAS rate was set to 5 kHz to minimize spinning sideband overlap. ¹H T₁ values were determined using a π/2-τ sequence by varying the duration of spin-locking pulses. The widths of the π/2 pulse used to measure the T₁ values of ¹H in (NH₄)₂ZnCl₄ and (NH₄)₂ZnBr₄ were 4.35 μs and 3.7 μs, respectively, with the spin-locking field equaling 57.47 kHz and 67.56 kHz.
In addition, the $^{14}$N NMR spectra of the (NH$_4$)$_2$ZnCl$_4$ and (NH$_4$)$_2$ZnBr$_4$ single crystals in the laboratory frame were measured using a Unity INOVA 600 NMR spectroscopy at the Korea Basic Science Institute, Western Seoul Center. The static magnetic field was 14.1 T, and the Larmor frequency was set to $\omega_0/2\pi = 43.342$ MHz. The $^{14}$N NMR experiments were performed using a solid echo sequence of $\pi/2$–$t$–$\pi/2$–$t$. The widths of the $\pi/2$ pulse for $^{14}$N in (NH$_4$)$_2$ZnCl$_4$ and (NH$_4$)$_2$ZnBr$_4$ were 4 $\mu$s and 3.7 $\mu$s, respectively. The measurements of $^1$H MAS NMR in the rotating frame and $^{14}$N NMR in the laboratory frame were obtained over the temperature range of 180–430 K. Sample temperatures on MAS NMR and static NMR were held constant within $\pm 0.5$ K by controlling the helium gas flow and heater current.

3. Experimental results and discussion

3.1 Phase transition temperatures

The phase transition temperatures for (NH$_4$)$_2$ZnCl$_4$ and (NH$_4$)$_2$ZnBr$_4$ single crystals have not yet been accurately established, as shown in Fig. 2. Here, the small vertical bars were represented the phase transition temperatures reported by several groups. In the case of (NH$_4$)$_2$ZnCl$_4$, this crystal exhibits three temperature dependence anomalies in the dielectric, thermal, and X-ray diffraction measurements at 270 K, 319 K, and 406 K, respectively, as reported by Matsunaga et al. Furthermore, anomalies characteristic of phase transitions reported by Agarwal et al. have been found in the Raman spectra investigations at 194 K, 266 K, 271 K, 319 K, and 406 K. According to Gillet et al., the occurrence of phase transitions at 253 K, 256 K, 319 K, 364 K, and 406 K was also confirmed on the basis of the Brillouin investigation. In addition, thermal expansion changes at temperatures of 253 K, 255 K, 323 K, 362 K, and 406 K were reported by Tylczynski et al. In the case of (NH$_4$)$_2$ZnBr$_4$, phase transition temperatures have been reported at 216 K, 395 K, and 432 K by Osaka et al., and an additional phase transition at 365 K was reported by Tylczynski et al. in their investigation of a (NH$_4$)$_2$ZnBr$_4$ crystal using $^{81}$Br nuclear quadrupole resonance (NQR), differential thermal analysis (DTA), and dielectric measurements. Fig. 2 shows that the phase transition temperatures obtained by several experiments are inconsistent for (NH$_4$)$_2$ZnCl$_4$ and (NH$_4$)$_2$ZnBr$_4$, respectively.

In order to determine the phase transition temperatures for the (NH$_4$)$_2$ZnCl$_4$ and (NH$_4$)$_2$ZnBr$_4$ single crystals obtained here, differential scanning calorimetry (DSC) measurements were taken with a DuPont 2010 DSC instrument at a heating rate of 10 °C min$^{-1}$. The DSC measurements revealed three endothermic peaks at 270 K, 320 K, and 406 K for (NH$_4$)$_2$ZnCl$_4$, and four endothermic peaks at 216 K, 362 K, 396 K, and 432 K for (NH$_4$)$_2$ZnBr$_4$, as shown in Fig. 3. These endothermic peaks were related to the phase transitions, and the temperatures were consistent with those previously reported by Matsunaga et al. and Moskalev et al. The phase transition temperatures of (NH$_4$)$_2$ZnX$_4$ may vary according to the conditions of crystal growth.

3.2 Molecular motion near phase transition temperatures from $^1$H MAS NMR

The $^1$H MAS NMR spectra in (NH$_4$)$_2$ZnCl$_4$ and (NH$_4$)$_2$ZnBr$_4$ were measured as a function of temperature. At room temperature, (NH$_4$)$_2$ZnCl$_4$ and (NH$_4$)$_2$ZnBr$_4$ showed only one peak each, at
chemical shifts of $\delta = 6.53$ ppm and $\delta = 6.66$ ppm, respectively, as shown in Fig. 4. The phase transition temperatures of $\text{(NH}_4\text{)}_2\text{ZnCl}_4$ are denoted by solid lines, and those of $\text{(NH}_4\text{)}_2\text{ZnBr}_4$ are denoted dash lines. The chemical shifts of the two materials did not change near the phase transition temperatures. The $^1\text{H}$ chemical shifts of $\text{(NH}_4\text{)}_2\text{ZnCl}_4$ decreased with increasing temperature, whereas the $^1\text{H}$ chemical shift of $\text{(NH}_4\text{)}_2\text{ZnBr}_4$ increased with increasing temperature. From the chemical shift for $^1\text{H}$, the proton environments in N–H–Cl bond and the proton environments in N–H–Br bond were very different. This difference of chemical shifts was possibly due to the difference between the electron structures of halogen ions.

The decay traces for the $^1\text{H}$ resonance line in $\text{(NH}_4\text{)}_2\text{ZnCl}_4$ and $\text{(NH}_4\text{)}_2\text{ZnBr}_4$ are represented by a single exponential function of $M(t) = M(\infty)\exp(-t/T_{1p})$, where $M(t)$ is the magnetization as a function of the spin-locking pulse duration $t$, and $M(\infty)$ is the total nuclear magnetization of $^1\text{H}$ at thermal equilibrium. The decay traces for the $^1\text{H}$ nuclei varied with the delay time, and these decay traces also varied depending upon the temperature. The decay traces fitted with the single exponential function for delay times. From the slopes of the decay traces, the $^1\text{H}$ spin-lattice relaxation times, $T_{1p}$, in the rotating frame for the $\text{(NH}_4\text{)}_2\text{ZnCl}_4$ and $\text{(NH}_4\text{)}_2\text{ZnBr}_4$ were obtained as a function of temperature, as shown in Fig. 5. The $T_{1p}$ values of $^1\text{H}$ were significantly different in the high-temperature and low-temperature regions. The significant difference in the $T_{1p}$ values indicates that $\text{(NH}_4\text{)}_2\text{ZnCl}_4$ and $\text{(NH}_4\text{)}_2\text{ZnBr}_4$ are strongly affected, which considered to be mainly the result of molecular motions. The $^1\text{H}$ $T_{1p}$ data showed no evidence of a change near the phase transition temperatures. The trend of $^1\text{H}$ $T_{1p}$ in $\text{(NH}_4\text{)}_2\text{ZnCl}_4$ resembled that of $^1\text{H}$ $T_{1p}$ in $\text{(NH}_4\text{)}_2\text{ZnBr}_4$. The two $T_{1p}$ series displayed similar trends, both decreasing quickly above 310 K. The variation of $T_{1p}$ with temperature exhibited a shallow minimum of 7.2 ms at 430 K in the case of $\text{(NH}_4\text{)}_2\text{ZnBr}_4$, indicating that distinct molecular motion is present. The $T_{1p}$ minimum is considered to be clearly attributable to the tumbling motion of $\text{NH}_4^+$ ions. The $T_{1p}$ values are related to the corresponding values of the rotational correlation time, $\tau_{\text{C}}$. 

Fig. 2 Phase transition temperatures (K) for $\text{(NH}_4\text{)}_2\text{ZnX}_4$ ($X = \text{Cl}, \text{Br}$) reported by several groups.

Fig. 3 Differential scanning calorimetry (DSC) thermograms of $\text{(NH}_4\text{)}_2\text{ZnCl}_4$ and $\text{(NH}_4\text{)}_2\text{ZnBr}_4$ single crystals.

Fig. 4 Chemical shifts of $^1\text{H}$ MAS NMR spectra in $\text{(NH}_4\text{)}_2\text{ZnCl}_4$ and $\text{(NH}_4\text{)}_2\text{ZnBr}_4$ as a function of temperature (($\text{NH}_4\text{)}_2\text{ZnCl}_4$: solid lines, $\text{(NH}_4\text{)}_2\text{ZnBr}_4$: dash lines).
which directly measures the rate of motion. The experimental $T_{1\rho}$ value can be expressed in terms of $\tau_c$ using molecular motion, as suggested by the Bloembergen–Purcell–Pound (BPP) theory.23 The $T_{1\rho}$ value in the rotating frame can also be expressed in terms of $\tau_c$ using molecular motion,28,34

$$1/T_{1\rho} = (n/20)\left(\gamma_H \gamma_N r_{\text{H-N}}^2\right)\left[4f(\omega_H) + f(\omega_H - \omega_N) + 3f(\omega_N)ight] + 6f(\omega_H + \omega_N) + 6f(\omega_H)] \quad (1)$$

Here:

$$f(\omega) = \tau_c/[1 + \omega^2 \tau_c^2]$$

$$f(\omega_H - \omega_N) = \tau_c/[1 + (\omega_H - \omega_N)^2 \tau_c^2]$$

$$f(\omega_N) = \tau_c/[1 + \omega_N^2 \tau_c^2]$$

$$f(\omega_H + \omega_N) = \tau_c/[1 + (\omega_H + \omega_N)^2 \tau_c^2]$$

$$f(\omega_H) = \tau_c/[1 + \omega_H^2 \tau_c^2]$$

In the equation, $\gamma_H$ and $\gamma_N$ are the gyromagnetic ratios for the $^1$H and $^{14}$N nuclei, respectively; $n$ is the number of directly bound protons; $r_{\text{H-N}}$ is the H–N internuclear distance; $h$ is the reduced Planck constant; $\omega_H$ and $\omega_N$ are the Larmor frequencies of $^1$H and $^{14}$N, respectively; and $\omega_1$ is the spin-lock field frequency of 67.56 kHz. Here, the $f(\omega_1)$ is non-zero, i.e., the $\tau_c$ is much less than the Larmor frequencies, therefore all of the other terms is far smaller than the $f(\omega_1)$ term. We analyzed our data by assuming that $T_{1\rho}$ would show a minimum when $\omega_1\tau_c = 1$, and that the relation between $T_{1\rho}$ and the characteristic frequency of motion, $1/\tau_c$, could be applied. The coefficient in eqn (1) can be determined because the $T_{1\rho}$ curve displays a minimum and because the value of $\tau_c$ can be obtained from $\omega_1\tau_c = 1$; thus, $(n/20)(\gamma_H \gamma_N r_{\text{H-N}}^2) = 4.66 \times 10^6$ in the BPP formula. We were then able to calculate the correlation time $\tau_c$ as a function of temperature. The temperature dependence of $\tau_c$ follows a simple Arrhenius expression:

$$\tau_c = \tau_o \exp(-E_c/RT), \quad (2)$$

where $\tau_o$ is a pre-exponential factor, $T$ is the temperature, $R$ is the gas constant, and $E_c$ is an activation energy. Thus, the slope of the linear portion of a semi-logarithmic plot should yield $E_c$. The value of $E_c$ for the tumbling motion can be obtained from a fit to a log $\tau_c$ versus 1000/T. We obtained $E_c = 36.69 \pm 0.66$ kJ mol$^{-1}$ for the tumbling motion of $^1$H in (NH$_4$)$_2$ZnBr$_4$ at high temperature. This value is very similar to that for $^1$H in (NH$_4$)$_2$ZnCl$_4$, and is within the error range. And, the $E_c$ for (NH$_4$)$_2$ZnCl$_4$ and (NH$_4$)$_2$ZnBr$_4$ at low temperature is 0.32 ± 0.30 kJ mol$^{-1}$ and 2.25 ± 0.37 kJ mol$^{-1}$, respectively.

On the other hand, the $^1$H spin-lattice relaxation time $T_1$ in the laboratory frame in (NH$_4$)$_2$ZnCl$_4$ previously reported was obtained as a function of temperature, as described by the BPP theory.23 The activation energy in the low and high temperature regions was reported 29.95 ± 0.85 kJ mol$^{-1}$ and 10.99 ± 0.37 kJ mol$^{-1}$, respectively.

### 3.3 Structural changes near phase transition temperatures from $^{14}$N NMR

In order to investigate local phenomena related to successive phase transitions, the NMR spectra of $^{14}$N ($I = 1$) was obtained as a function of temperature using static NMR at a Larmor frequency of $\omega_0/2\pi = 43.342$ MHz. $^{14}$N ($I = 1$) NMR is a sensitive method for probing local structural properties in each phase. The $^{14}$N NMR spectra consisted of pairs of lines at frequencies corresponding to the transitions $\Delta m = \pm 1 \leftrightarrow \Delta m = 0$. The crystal was oriented such that the magnetic field was aligned with the crystallographic c-axis. Temperature-dependent changes in the $^{14}$N resonance frequency are generally attributed to changes in the structural geometry, indicating a change in the quadrupole coupling constant of the $^{14}$N nuclei. The $^{14}$N NMR spectra at phase I, II, III, IV, and VI in (NH$_4$)$_2$ZnCl$_4$ crystals were plotted in Fig. 6. Here, the $^{14}$N peaks positions were denoted by close circles. Two resonance lines were expected because of the quadrupole interaction of the $^{14}$N nucleus. However, many resonance lines were observed, and they were much narrower in line width. The resonance frequencies of $^{14}$N signals in (NH$_4$)$_2$ZnCl$_4$ and (NH$_4$)$_2$ZnBr$_4$ single crystals are respectively plotted in Fig. 7(a) and (b) as a function of temperature. In the case of (NH$_4$)$_2$ZnCl$_4$, the phase transitions occurring at $T_{C1}$, $T_{C3}$, and $T_{C4}$ were observed from our DSC results, whereas those at $T_{C2}$ and $T_{C5}$ were not observed. Therefore, $T_{C1}$, $T_{C3}$, and $T_{C4}$ are denoted by solid lines, and $T_{C2}$ and $T_{C5}$ are denoted dotted lines in Fig. 7(a).
The resonance frequencies near $T_{C1}$, $T_{C4}$, and $T_{C5}$ changed, whereas those near $T_{C2}$ and $T_{C3}$ did not change. In phase I, each unit cell contains four formula units, and there are also two different kinds of $^{14}$N nuclei, termed N(1) and N(2). Therefore, the $^{14}$N NMR spectra exhibited eight resonance lines in four pairs. Here, the two inequivalent sites N(1) and N(2) are distinguished by the quadrupole coupling constant previously reported: $\frac{e^2qQ}{h} = 105.5$ kHz and $\eta = 0.96$ for N(1), and $\frac{e^2qQ}{h} = 48.2$ kHz and $\eta = 0.087$ for N(2). Additional lines in phases II, III, and IV were obtained, although they exhibited very small intensities compared with phase I. In phases III and IV, the unit cell is quadrupoled along the $c$-direction of phase I. The unit cell of phases III and IV contains 16 formula units, and thus 32 resonance lines of 16 pairs are expected. According to the crystallography results shown in Fig. 1(b), eight atoms N(11), N(21), N(31), and N(41) are surrounded by five Cl atoms, while the other atoms N(12), N(22), N(32), and N(42), which are located between the layers created by the ZnCl$_4$ tetrahedra, are surrounded by eight Cl atoms. From the NMR spectra results of 16 pairs of $^{14}$N, the approximately 32 resonance lines in phases III and IV were measured, as shown in Fig. 7(a). The 32 resonance lines from the 16 pairs of $^{14}$N in the NH$_4$ ion were consistent with the previously reported crystallography structure. In addition, phase VI, below $T_{C5}$, contains $Z = 12$ formula units, N(11), N(12), N(21), N(22), N(31), and N(32), as shown in Fig. 1(c). Therefore, approximately 24 resonance lines
in 12 pairs were obtained. In these results, the splitting of the $^{14}\text{N}$ resonance lines for seven of the pairs slightly decreased with increasing temperature, whereas those of the $^{14}\text{N}$ resonance lines for the other five pairs slightly increased with increasing temperature. On the other hand, the resonance frequencies in phases I, II, III, and IV for the case of (NH$_4$)$_2$ZnBr$_4$ are shown in Fig. 7(b). The $^{14}\text{N}$ NMR spectra from (NH$_4$)$_2$ZnBr$_4$ could not be easily observed in detail because of their very low intensity. However, the resonance frequencies near $T_{C2}$ and $T_{C3}$ changed discontinuously.

As mentioned above, in the case of (NH$_4$)$_2$ZnCl$_4$, four pairs of lines ascribed to N(1) and N(2) nuclei appeared in phase I, above 406 K. Because the frequency distributions in phase II discontinuously emerged from these high-temperature lines, the notations N(1) and N(2) were not retained. Based on this temperature dependence, the assignment of the resonance lines in phases III and IV are also not denoted. The resonance frequency from phase V cannot be distinguished because of the much narrower temperature range. The resonance frequencies in phase VI, below $T_{C4}$ and $T_{C3}$ changed discontinuously.

4. Conclusion

Data on structural geometries near successive phase transition temperatures of (NH$_4$)$_2$ZnX$_4$ (X = Cl, Br) were obtained by $^1\text{H}$ MAS NMR and $^{14}\text{N}$ NMR as a function of temperature. We studied the molecular motions in (NH$_4$)$_2$ZnX$_4$, based on the $^1\text{H}$ chemical shifts and spin-lattice relaxation time, $T_{1\rho}$, in the rotating frame. The $^1\text{H}$ chemical shifts near the phase transition temperatures for the two materials did not show any drastic change, and this result might be related to proton ordering near the phase transition temperatures. From the $^1\text{H}$ $T_{1\rho}$ results, the activation energies for the tumbling motion of $^1\text{H}$ had very similar values, and the tumbling motion of NH$_4^+$ ions occurred within the high-temperature range.

We compared the $^1\text{H}$ MAS NMR in the rotating frame measured here and the previously reported $^1\text{H}$ static NMR results in the laboratory frame$^{23-25}$ for (NH$_4$)$_2$ZnCl$_4$. The trends in $T_{1\rho}$ values for $^1\text{H}$ in (NH$_4$)$_2$ZnCl$_4$ are different from the trends in the $T_1$ values. The molecular motion by $T_{1\rho}$ in the rotating frame was dominant at high temperature, whereas that by $T_1$ in the laboratory frame was dominant at low temperature. The activation energy values extracted from $T_{1\rho}$ and $T_1$ measurements are different for the molecular motions in the kHz and MHz ranges.

The $^{14}\text{N}$ NMR spectra exhibited a sudden shift in the $^{14}\text{N}$ peak positions and number of peaks at the phase transition temperatures. The electric field gradient (EFG) tensors at the N sites varied, reflecting the changing atomic configurations around the $^{14}\text{N}$ nuclei. This is because the phase transition temperature strongly affects the $^{14}\text{N}$ number of symmetry related nitrogen centers within the unit cell. Therefore, $^{14}\text{N}$ NMR provides insight into changes in crystal symmetry and cation reorientation rates induced by heating and phase transitions.

The two crystals have different phase transition temperatures, but seemingly similar phase transition mechanisms. Although (NH$_4$)$_2$ZnX$_4$ has different bond lengths in the Zn–X (X = Cl, Br) structure, and different X atomic radii, the different halide ions (X = Cl, Br) do not appear to significantly influence the $^1\text{H}$ relaxation time.
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