Ionic dynamics of the cation in organic–inorganic hybrid compound (CH$_3$NH$_3$)$_2$MCl$_4$ ($M = $ Cu and Zn) by $^1$H MAS NMR, $^{13}$C CP MAS NMR, and $^{14}$N NMR

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The ionic dynamics of (CH$_3$NH$_3$)$_2$MCl$_4$ ($M = $ Cu, Zn) by $^1$H magic-angle spinning (MAS) nuclear magnetic resonance (NMR), $^{13}$C cross-polarization (CP) MAS NMR, and $^{14}$N NMR are investigated as a function of temperature with a focus on the role of the CH$_3$NH$_3^+$ cation. The molecular motions in (CH$_3$NH$_3$)$_2$MCl$_4$ are also discussed based on the $^1$H spin–lattice relaxation time in the rotating coordinate frame $T_1$. From the $^1$H $T_1$ results, the activation energies for the tumbling motion of $^1$H for CH$_3$ and NH$_3$ were similar, and the uniaxial rotations occurred within a large temperature range. The molecular motions for $^{13}$C and $^{14}$N of the main chain in the CH$_3$NH$_3^+$ cation were rigid, whereas those for $^1$H of the side chain in the CH$_3$NH$_3^+$ cation were very free at high temperatures. $T_1$ provides insight into the changes in the cation reorientation rates induced by heating at high temperatures.

1. Introduction

Hybrid organic–inorganic compounds have been known since 1976 but recently they have been revisited due to their potential use as substitute materials for perovskites. Metal complexes with the formula (CH$_3$NH$_3$)$_2$MCl$_4$ ($M = $ Mn, Fe, Cu, Zn, Cd) can be classified into two groups from a crystal structure point of view. One group [(CH$_3$NH$_3$)$_2$CuCl$_4$ ($M = $ Mn, Fe, Cd)] has a perovskite-type layer structure consisting of cationic layers and layers of corner-sharing chlorine octahedra with a divalent metal ion at the center. These compounds are characterized by a two-dimensional metal–chlorine network widely separated from one another by methyl ammonium groups. The metal ions are surrounded by a slightly distorted chlorine octahedron, Cl$_6$. The other group, to which (CH$_3$NH$_3$)$_2$CuCl$_4$ belongs, consists of discrete CH$_3$NH$_3^+$ and MCl$_4^{2-}$ ions packed in an arrangement similar to orthorhombic K$_2$SO$_4$-like members. In these crystals, unassociated Cl$_4$ tetrahedra are presented instead of corner-sharing layers of chlorine octahedra. Hydrogen-bonding takes place between the hydrogens of CH$_3$NH$_3^+$ and Cl$,^-$ and the several different possible hydrogen-bond configurations can give rise to structural phase transitions. The (CH$_3$NH$_3$)$_2$CuCl$_4$ compound with $M = $ Cu undergoes a structural phase transition at 348 K ($= T_c$), with the respective phases denoted as orthorhombic structure at high temperatures and monoclinic structure at room temperature. A sharp peak at 230 K from a thermal capacity experiment was also reported by White and Staveley. In the case of (CH$_3$NH$_3$)$_2$ZnCl$_4$ with $M = $ Zn, the existence of a phase transition at 483 K ($= T_c$) was reported by calorimetric, dielectric, thermal expansion, and optical measurements. However, a transition at 426 K ($= T'_c$) was reported from Raman and IR spectra but not by differential scanning calorimetry (DSC), differential thermal analysis (DTA), and $^1$H nuclear magnetic resonance (NMR) measurements. The structure of (CH$_3$NH$_3$)$_2$ZnCl$_4$ is orthorhombic at high temperatures and monoclinic at low temperatures. In addition, it has been reported from low-temperature DSC that a phase transition exists at 265 K during heating.

Following previous NMR investigations, the spin–lattice relaxation time $T_1$ of $^1$H in the CH$_3$ and NH$_3$ groups of (CH$_3$NH$_3$)$_2$CuCl$_4$ at the Larmor frequencies of 12 and 26 MHz was reported. The spectra of the two groups overlap at high temperatures and separate at low temperatures. The $T_1$ at low temperatures exhibits a strong temperature dependence. Moreover, the self-diffusion and reorientation of the methylammonium ions in (CH$_3$NH$_3$)$_2$ZnCl$_4$ was reported by $^1$H NMR. In addition, the spin–spin relaxation time $T_2$ of $^{63}$Cu and $^{35}$Cl in (CH$_3$NH$_3$)$_2$CuCl$_4$ has been reported at 1.75 K. In the case of (CH$_3$NH$_3$)$_2$ZnCl$_4$, $^1$H $T_1$ NMR studies at the Larmor frequency of 20 MHz revealed that the cation in the highest-temperature phase performs isotropic rotation and self-diffusion. The cation in the low-temperature phase undergoes reorientation about its C–N bond axis. Although the structural phase transitions in (CH$_3$NH$_3$)$_2$CuCl$_4$ and (CH$_3$NH$_3$)$_2$ZnCl$_4$ have been performed by several research groups, the corresponding molecular motions and structural geometry changes have not been fully studied by NMR in the rotating frame.
In the present study, to clarify the ionic dynamics of CH$_3$NH$_3^+$ cations and to also obtain information of the mechanism of the phase transition in (CH$_3$NH$_3$)$_2$MCl$_4$ (M = Cu, Zn), the chemical shifts and spin–lattice relaxation time in the rotating coordinate frame $T_{1p}$ were measured as a function of temperature using $^1$H magic-angle spinning (MAS) NMR and $^{13}$C cross-polarization (CP) MAS NMR. In addition, the $^{14}$N NMR spectra in (CH$_3$NH$_3$)$_2$ZnCl$_4$ single crystals in the laboratory frame were discussed in order to elucidate the structural geometry. We focus on the structural phase transitions of compounds with the formula (CH$_3$NH$_3$)$_2$MCl$_4$. We use these geometry. We focus on the structural phase transitions of compounds with the formula (CH$_3$NH$_3$)$_2$MCl$_4$. We use these compounds to also obtain information of the mechanism of the phase transition in (CH$_3$NH$_3$)$_2$MCl$_4$ (M = Cu, Zn) previously reported.

2. Materials and methods

2.1. Crystal structure

The (CH$_3$NH$_3$)$_2$CuCl$_4$ undergoes a phase transition at 348 K. At temperatures below $T_C = 348$ K, the structure is monoclinic, the space group is $P2_1/c$, and the lattice constants are $a = 7.155$ Å, $b = 7.424$ Å, $c = 9.814$ Å, and $\beta = 109.18^\circ$. The crystal structure at 363 K is orthorhombic, the space group is $Cmnb$, and the lattice constants are $a = 7.34$ Å, $b = 18.71$ Å, and $c = 7.33$ Å. The monoclinic structure at room temperature is shown in Fig. 1. Here, the methylammonium moieties are located between the layers and are connected by hydrogen bonds to the Cl$^-$ ions. Further, (CH$_3$NH$_3$)$_2$ZnCl$_4$ undergoes a phase transition at 483 K. At room temperature, the crystal is monoclinic with the space group $P2_1/c$, and the lattice constants are $a = 10.873$ Å, $b = 12.655$ Å, $c = 7.648$ Å, $\beta = 96.71^\circ$, and $Z = 4$. Here, the two inequivalent sites, CH$_3$(1) and CH$_3$(2), and NH$_3$(1) and NH$_3$(2), in (CH$_3$NH$_3$)$_2$ZnCl$_4$ were reported by Morosin et al.

2.2. Experimental method

Single crystals of (CH$_3$NH$_3$)$_2$MCl$_4$ (M = Cu, Zn) were prepared by the slow evaporation of an aqueous solution of stoichiometric amounts of CH$_3$NH$_3$HCl and MCl$_2$ (M = Cu, Zn) at room temperature. The color of (CH$_3$NH$_3$)$_2$MCl$_4$ single crystals is brown with flat parallelepipeds. In addition, (CH$_3$NH$_3$)$_2$ZnCl$_4$ single crystals are colorless and transparent with a square shape. The phase transition temperatures were determined using DSC (Dupont, 2010) measurements at a heating rate of 10 K min$^{-1}$.

$^1$H MAS NMR and $^{13}$C CP MAS NMR spectra of (CH$_3$NH$_3$)$_2$MCl$_4$ (M = Cu, Zn) in the rotating coordinate frame were obtained at the Larmor frequencies of $\omega_0/2\pi$ = 400.13 and 100.61 MHz, respectively, using a Bruker 400 MHz NMR spectrometer at the Korea Basic Science Institute, Western Seoul Center. Powdered samples were placed in a 4 mm CP MAS probe, and the MAS rate was set to 10 kHz for both $^1$H MAS and $^{13}$C CP MAS measurements to minimize the spinning sideband overlap. The chemical shifts were referred with respect to tetramethylsilane (TMS). The spin–lattice relaxation times for $^1$H and $^{13}$C of (CH$_3$NH$_3$)$_2$ZnCl$_4$ in the rotating coordinate frame were determined using a π/2 – t sequence by varying the duration of the spin-locking pulses. In the case of (CH$_3$NH$_3$)$_2$CuCl$_4$, the width of the π/2 pulse used for measuring the $T_{1p}$ values of $^1$H and $^{13}$C was 3.9 μs, with a spin-locking field of 64.1 kHz. In the case of (CH$_3$NH$_3$)$_2$ZnCl$_4$, the width of the π/2 pulse used for measuring the $T_{1p}$ values of $^1$H and $^{13}$C was 4.5 and 5.6 μs, with the spin-locking field of 55.55 kHz and 44.64 kHz, respectively. The power level for $^1$H and $^{13}$C was 4 dB and 6.5 dB, respectively. The $^{13}$C $T_{1p}$ values were measured by varying the duration of the $^{13}$C spin-locking pulse applied after the CP preparation period.

In addition, the $^{14}$N NMR spectra of the (CH$_3$NH$_3$)$_2$ZnCl$_4$ single crystals in the laboratory frame were measured using a Unity INOVA 600 NMR spectrometer at the same facility. 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 conducted using a solid-echo pulse sequence.

Temperature-dependent NMR spectra were recorded at 180–430 K as the chemical shift and relaxation time could not be determined outside this temperature range, because of the limitations of the spectrometer used. The sample temperatures were maintained within ±0.5 K by controlling the nitrogen gas flow and heater current.

3. Results and discussion

The DSC analysis in (CH$_3$NH$_3$)$_2$CuCl$_4$ revealed two endothermic peaks at 347 K (= $T_C$) and 517 K (= $T_m$) related to the phase
transition and melting point, respectively, as shown in Fig. 2. The enlarged peak near 347 K in Fig. 2 is very small relative to the other endothermic peak. In the case of (CH$_3$NH$_3$)$_2$ZnCl$_4$, two endothermic peaks are obtained at 475 K ($= T_c$) and 525 K ($= T_m$), which are due to the phase transition and melting point. In order to understand the additional endothermic peaks at high temperature, we conduct optical polarizing microscopy. The peaks of 517 and 525 K in (CH$_3$NH$_3$)$_2$CuCl$_4$ and (CH$_3$NH$_3$)$_2$ZnCl$_4$, respectively, are not related to physical changes such as structural phase transitions; they are instead related to the melting point. The phase transition temperatures obtained here are consistent with previous results.$^{21,23}$ This suggests that the differences in the chemical properties of Cu and Zn are responsible for the variations of the phase transition temperatures $T_c$ in the two crystals.

The NMR spectra for $^1$H in (CH$_3$NH$_3$)$_2$MCl$_4$ (M = Cu, Zn) were recorded by MAS NMR at a frequency of 400.13 MHz. In the case of the two compounds, the spectrum of the two peaks is assigned to the $^1$H in CH$_3$ and NH$_3$. One of them, the spectrum of the two peaks at chemical shifts of $\delta = 3.82$ and 12.52 in (CH$_3$NH$_3$)$_2$CuCl$_4$ at room temperature, is presented in Fig. 3. Here, the unit of the NMR scale is represented according to the IUPAC convention.$^{33,34}$ The spinning sidebands for CH$_3$ are marked with open circles and those for NH$_3$ are marked with crosses. The line component of the lower chemical shift is attributed to the $^1$H in CH$_3$, and that of the higher chemical shift is attributed to the $^1$H in NH$_3$. The protons of CH$_3$ and NH$_3$ are distinguished from the $^1$H chemical shifts. In the case of (CH$_3$NH$_3$)$_2$CuCl$_4$ across the phase transition temperature of $T_c$, the chemical shift slowly and monotonously decreases with temperature, indicating that the environments of the surrounding $^1$H in the CH$_3$ and NH$_3$ groups change continuously (see Fig. 4(a)). However, the proton spectrum of the two peaks in (CH$_3$NH$_3$)$_2$ZnCl$_4$ at room temperature is recorded at chemical shifts of $\delta = 2.88$ and 6.75. The $^1$H chemical shifts in (CH$_3$NH$_3$)$_2$ZnCl$_4$ are almost constant with temperature, as shown in Fig. 4(b).

The $^1$H spin–lattice relaxation times in the rotating coordinate frame of (CH$_3$NH$_3$)$_2$MCl$_4$ (M = Cu, Zn) were obtained for the CH$_3$ and NH$_3$ at several temperatures. The nuclear magnetization decay of $^1$H follows a single exponential function. Thus, $T_{1p}$ can be determined by fitting the traces with the following equation:$^{35}$

$$S(t)/S(\infty) = \exp(-t/T_{1p}),$$

where $S(t)$ is the magnetization with the spin-locking pulse duration $t$ and $S(\infty)$ is the total nuclear magnetization of $^1$H at thermal equilibrium. The values of $^1$H $T_{1p}$ for two compounds in the rotating coordinate frame between 180 and 430 K are shown in Fig. 5(a) and (b) as a function of the inverse temperature. The $T_{1p}$ values for the methyl protons and ammonium protons in the CH$_3$NH$_3^+$ cations exhibit similar trends with temperature. The $T_{1p}$ values of $^1$H in the CH$_3$ and NH$_3$ groups of (CH$_3$NH$_3$)$_2$CuCl$_4$ are almost continuous near $T_c$, and these values are of the order of milliseconds. Above 400 K, the two $T_{1p}$ values abruptly decrease, and the $^1$H $T_{1p}$ values for CH$_3$ are longer than those for NH$_3$. In contrast, the significant change in the $^{13}$C $T_{1p}$ values of (CH$_3$NH$_3$)$_2$ZnCl$_4$ is strongly affected, which is primarily considered the result of molecular motions. Further, the variation of $T_{1p}$ with temperature exhibits a minimum of 16.3 and 12.8 ms for CH$_3$ and NH$_3$ near 400 K, respectively. This behavior of $T_{1p}$ indicates that distinct molecular motions are present. It is clear that the minimum $T_{1p}$ is attributable to the uniaxial rotation of CH$_3$ and NH$_3$ ions. The experimental value of $T_{1p}$ is expressed in terms of the isotropic correlation time $\tau_c$ for molecular motion using the Bloembergen–Purcell–Pound (BPP) theory,$^{36,40}$ according to which the $T_{1p}$ value for a spin–lattice interaction of molecular motion is given by$^{37-39}$

$$\tau_c^{-1} = 0.05(\mu_0/4\pi)^2 (\gamma_H^2) (r_{CH_3}^3)^3 [4a + 6b + 3c + 6d + 6e],$$

Fig. 2 Differential scanning calorimetry thermogram of (CH$_3$NH$_3$)$_2$CuCl$_4$ and (CH$_3$NH$_3$)$_2$ZnCl$_4$ single crystals.

Fig. 3 $^1$H MAS NMR spectra of (CH$_3$NH$_3$)$_2$CuCl$_4$ at 300 K (the spinning sidebands are marked with crosses and open circles).
where \( a = \tau_C [1 + \omega_1^2 \tau_C^2] \), \( b = \tau_C [1 + (\omega_H - \omega_C)^2 \tau_C^2] \), \( c = \tau_C [1 + \omega_C^2 \tau_C^2] \), \( d = \tau_C [1 + (\omega_H + \omega_C)^2 \tau_C^2] \), and \( e = \tau_C [1 + \omega_1^2 \tau_C^2] \). Here, \( \mu_0 \) is the permeability constant, \( \gamma_H \) and \( \gamma_C \) are the gyromagnetic ratios for the \(^1\)H and \(^{13}\)C nuclei, respectively, \( n \) is the number of directly bound protons, \( r \) is the H–C internuclear distance, \( \hbar = h / 2\pi \) (where \( h \) is Planck’s constant), \( \omega_H \) and \( \omega_C \) are the Larmor frequencies of \(^1\)H and \(^{13}\)C, respectively, and \( \omega_1 \) is the spin-lock field of 55.55 kHz. Our data are analyzed assuming \( T_{1\rho} \) shows a minimum when \( \omega_C \tau_C = 1 \) and the BPP relation between \( T_{1\rho} \) and \( \omega_1 \) is applicable. As the \( T_{1\rho} \) curves are found to exhibit minima, it was possible to determine the coefficient, \( 0.05(\mu_0^3/4\pi^2) (\gamma_H\gamma_C h/\tau_1)^3 \), in the BPP formula. With this coefficient determined, we were then able to calculate the parameter \( \tau_C \) as a function of temperature. The temperature dependence of \( \tau_C \) follows a simple Arrhenius expression, \( \tau_C = \tau_{0C} \exp(-E_A/RT) \), where \( \tau_{0C} \) is the pre-exponential factor, \( T \) is the temperature, \( R \) is the gas constant, and \( E_A \) is the activation energy. Thus, the slope of the straight-line portion of the semi-log plot can be used to determine \( E_A \). The activation energy for the uniaxial rotation of CH₃ and NH₃, obtained from the log \( \tau_C \) vs. 1000/T curve shown in the inset of Fig. 5(b), is 19.72 ± 1.10 and 19.88 ± 0.89 kJ mol⁻¹, respectively, and is the same within the error range. In addition, the \( E_A \) value for CH₃ and NH₃ at temperatures below 200 K is 6.59 ± 0.51 and 5.92 ± 0.40 kJ mol⁻¹, respectively. The chemical shifts for \(^{13}\)C in \((\text{CH₃NH₃})_2\text{CuCl}_4\) were measured as a function of temperature, as shown in Fig. 6. At room temperature, the \(^{13}\)C CP MAS NMR spectrum shows a signal at a chemical shift of \( \delta = 190.5 \) with respect to TMS. The \(^{13}\)C chemical shift slowly and monotonously decreases with temperature. In contrast, the chemical shifts for \(^{13}\)C in \((\text{CH₃NH₃})_2\text{ZnCl}_4\) were also measured over the temperature range of 180 to 430 K, as shown in the inset of Fig. 6. At room temperature, the \(^{13}\)C CP MAS NMR spectrum possesses two signals at chemical shifts of \( \delta = 27.82 \) and 29.02. These signals are attributed to the methyl carbons of the two inequivalent sites CH₃ (1) and CH₃ (2), and these results are consistent with the X-ray result previously reported:¹⁸ there exist two kinds of
With temperature. The $T_{1p}$ values around $T_C$ are unchanged, in agreement with the conclusion drawn from the $^{13}$C chemical shifts. In the case of \((CH_3NH_3)_2ZnCl_4\), the phase transition occurring at $T_C (= 426 \text{ K})$ reported by Perez-Mato et al.\cite{23} is not observed from our DSC results, whereas the changes near $T_C$ are observed by the $^{13}$C chemical shift and $^{13}$C $T_{1p}$ results. Thus, $T_C$ is denoted by dotted lines in the inset of Fig. 5, 6, and 8. The $T_{1p}$ values for the two $^{13}$C signals of CH$_3$ (1) and CH$_3$ (2) in \((CH_3NH_3)_2ZnCl_4\) are almost the same within the experimental error range.

In order to obtain information concerning the possible distortion surrounding the $^{14}$N ion, the NMR spectrum of $^{14}$N ($I = 1$) in the laboratory frame was obtained using static NMR at a Larmor frequency of $\omega_0/2\pi = 43.342 \text{ MHz}$. Two resonance signals were expected from the quadrupole interactions of the $^{14}$N nucleus. A magnetic field was applied along the crystallographic axis. The in situ $^{14}$N NMR spectra and resonance frequency in \((CH_3NH_3)_2ZnCl_4\) single crystals are plotted.

![Graph](image)

**Fig. 6** $^{13}$C chemical shift in CH$_3$ groups in \((CH_3NH_3)_2CuCl_4\) as a function of temperature (inset: that in \((CH_3NH_3)_2ZnCl_4\) as a function of temperature).
NMR, 13C CP MAS NMR, and 14N NMR as a function of parameter of the 14N nuclei. The electric resonance frequency are generally attributed to changes in the spectra in (CH3NH3)2ZnCl4 single crystal as a function of temperature. The electric resonance frequency near 300 K is not related to the phase slightly decreases with temperature. The small change of the (inset: 14N NMR spectra as a function of temperature).

4. Conclusions

The ionic dynamics of (CH3NH3)2MCl4 (M = Cu, Zn), focusing on the role of the CH3NH3+ cation, were investigated by 1H MAS NMR, 13C CP MAS NMR, and 14N NMR as a function of temperature. We studied the molecular motions for 1H and 13C in (CH3NH3)2MCl4 (M = Cu, Zn) based on the spin–lattice relaxation time in the rotating coordinate frame. From the 1H T1p results, we found that the molecular motions for 1H in (CH3NH3)2CuCl4 are very active at high temperatures. In addition, the activation energies for the uniaxial rotation of 1H for the CH3 and NH3 ions in (CH3NH3)2ZnCl4 have very similar values, and the uniaxial rotation occurs within the high-temperature range. The T1p results reveal that the CH3 and NH3 cations exhibit high mobility at high temperatures. The T1p provides insight into the changes in the cation reorientation rates induced by heating at high temperatures. On the other hand, the minima for (CH3NH3)2ZnCl4 are attributed to the uniaxial rotation of the CH3NH3 cations. However, minima such as T1p for (CH3NH3)2CuCl4 were not reached for that compound. The lack of a minimum T1p indicates that this motion is so slow that there was no detectable T1p temperature dependence and also that the uniaxial rotation in (CH3NH3)2CuCl4 was slower than that in (CH3NH3)2ZnCl4. The motion of the CH3NH3 cations is slower than the C1 internal rotation of CH3 and NH3; therefore, it reveals T1p minima in the high temperature regime above liquid nitrogen temperature. The minima related to the C3 rotation will appear in the low temperature regime.

A comparison with other compounds of the (CH3NH3)2MCl4 (M = Cu, Zn) indicates a different phase sequence for (CH3NH3)2MCl4 (M = Cd, Mn). For M = Cd, Mn, these systems at room temperature reveal orthorhombic symmetry followed by a tetragonal phase below room temperature. A phase with monoclinic symmetry is also reported at low temperatures. It is interesting to compare the results for (CH3NH3)2CuCl4 with those for the analogous compounds containing other metals. In the case of (CH3NH3)2MnCl4 and (CH3NH3)2CdCl4, there is an intermediate tetragonal phase between the monoclinic and orthorhombic phases.16,21 In contrast, the phase transition sequence for (CH3NH3)2CuCl4 and (CH3NH3)2ZnCl4 changes to an orthorhombic to monoclinic structure with decreasing temperature.22,23

The created magnetization decay for each proton in (CH3NH3)2CuCl4 (M = Cu, Zn) was analyzed by a single exponential function $S(t)/S(\infty) = A \exp(-t/T_{1p})$, whereas for each proton in (CH3NH3)2MCl4 (M = Mn, Cd) was analyzed by a double-exponential function $S(t)/S(\infty) = A \exp(-t/T_{1p}(s)) + B \exp(-t/T_{1p}(L))$. These results are consistent with the interactions between the CH3NH3 cations and its surrounding MCl4− anions. This difference of T1p is possibly due to the difference between the electron structures of metal ions. Cu2+ and Zn2+ have one and two s electrons, respectively, outside the closed d shell; Mn2+ has two s electrons in the unfilled 3d orbital; Cd2+ has two electrons outside the closed d shell.

The T1p values for 1H of CH3 and NH3 indicate that the protons in the CH3NH3 cations that are involved in the hydrogen bonding exhibit large and small T1p values corresponding to the long C–H and short N–H bonds, respectively. The molecular motion of the cation is induced by heating at high temperatures. The cation dynamics and interionic interactions through hydrogen bonds are expected to be closely related with the physical properties due to the potential
applications. We will be examined the effect for lengths of alkyl chains as further study.

Conflicts of interest

There are no conflicts to declare.

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