Pressure dependence of magnetic transition temperature in $\text{Li}[\text{Li}_x\text{Mn}_{2-x}]\text{O}_4$ ($0 \leq x \leq 1/3$) studied by muon-spin rotation and relaxation

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In order to study a change in electrochemical, structural, and magnetic properties for lithium manganese oxide spinels $\text{Li}[\text{Li}_x\text{Mn}_{2-x}]\text{O}_4$ (LMO) with $0 \leq x \leq 1/3$, muon-spin rotation and relaxation (μSR) spectra were recorded under pressure (P) up to 2.1 GPa. At ambient P , $P = 0.1$ MPa, the antiferromagnetic or spin-glass-like transition temperature (T_m) at $P = 0.1$ MPa monotonically decreases with increasing x . On the contrary, the slope of the T_m vs. P (dT_m/dP) rapidly increases from 0.9(1) K/GPa at $x = 0$ to 1.4 K/GPa at $x = 0.1$, then drops to 0.7(1) K/GPa at $x = 0.15$, and finally keeps constant (~ 0.4 K/GPa) with further increasing x . Considering the structural change of LMO with x , the decrease in the distance between Mn ions ($d_{\text{Mn-Mn}}$) is likely to play an essential role for determining T_m under P . According to cyclic voltammetry on LMO, the peak current at both anodic and cathodic directions shows the maximum at $x = 0.1$, indicating the highest diffusivity of Li^+ ions (D_{Li}) at $x = 0.1$. © 2013 American Institute of Physics. [<http://dx.doi.org/10.1063/1.4790377>]

I. INTRODUCTION

A spinel-type lithium manganese oxide $\text{Li}[\text{Li}_x\text{Mn}_{2-x}]\text{O}_4$ (LMO) with $0 \leq x \leq 1/3$ has attracted much attention as a positive electrode material of lithium-ion batteries (LIB), due to a reversible Li extraction and insertion reaction.¹ At room temperature (T), LMO has a cubic structure with a space group of $Fd\bar{3}m$, in which Li^+ ions occupy both tetrahedral $8a$ and octahedral $16d$ sites, while $\text{Mn}^{3+}/\text{Mn}^{4+}$ ions sit in the octahedral $16d$ site [see Fig. 1(a)]. Since the average valence of Mn ions increases from +3.5 at $x = 0$ to +4 at $x = 1/3$, the theoretical capacity based on a redox reaction of $\text{Li}[\text{Li}_x\text{Mn}_{2-x}]\text{O}_4 \leftrightarrow y\text{Li}^+ + y\text{e}^- + \text{Li}_{1-y}[\text{Li}_x\text{Mn}_{2-x}]\text{O}_4$ ($y = 1 - 3x$) decreases with increasing x . Although the electrochemical performance of LMO depends on an oxygen deficiency, particle size/morphology, and surface condition of the particle, there is a general agreement that the presence of a small amount of Li^+ ions at the $16d$ site improves the cycleability and rate capability of LMO.²⁻⁶

The structural and magnetic nature of LMO is also known to change drastically by a small amount of x .⁷⁻¹² The $x = 0$ compound exhibits a structural phase transition from a high- T cubic ($Fd\bar{3}m$) phase to a low- T orthorhombic ($Fddd$) phase at ~ 285 K ($=T_{\text{JT}}$), which is induced by a cooperative Jahn-Teller (JT) transition due to the Mn^{3+} ions with $t_{2g}^3e_g^1$ ($S = 2$).⁷ Differential calorimetry analyses⁸ indicated that, as x increases from 0, T_{JT} rapidly decreases down to ~ 214 K at $x = 0.035$, and finally disappears with further increasing x .

Moreover,⁷ Li-NMR,⁹ neutron scattering,¹⁰ and muon-spin rotation and relaxation (μSR)^{11,12} measurements clarified that the $x = 0$ compound shows an antiferromagnetic (AF) transition at $T_N \sim 60$ K, while the compound with $x \geq 0.05$ indicates a spin-glass-like transition below $T_f \sim 25$ K. Here, μSR is very sensitive to local magnetic environment and is a powerful technique for investigating both static and dynamic magnetic fields generated by nuclear- and electronic-magnetic moments.¹³

Since the deviations from stoichiometry in LiCoO_2 ^{14,15} and LiNiO_2 ¹⁶ also alter their electrochemical, structural, and magnetic properties, an in-depth-understanding of the lightly substituted LMOs that could lead to the further development of LIB materials. However, the roles of the Li^+ ions at the $16d$ site in LMO are still not fully understood, because the substitution of Li^+ ions for Mn^{3+} ions produces multiple variations in the LMO crystal lattice, e.g., decreases the cubic lattice parameter (a_c), modifies the ratio of $\text{Mn}^{3+}/\text{Mn}^{4+}$ ions, and changes the oxygen positional parameter (u). Note that u , for the $x = 0$ compound at room T , is reported to be ~ 0.385 ,² resulting in the distortion of the oxygen sub-lattice [see Fig. 1(b)]. We have, therefore, performed a systematic high-pressure (HP) μSR studies on LMO with $0 \leq x \leq 1/3$ up to the pressure (P) of 2.1 GPa. This is because P is one of the crucial parameters for determining structural and physical properties via the shrinkage of lattice parameters. In this paper, we report the P dependence of magnetic transition temperature (dT_m/dP) of LMO, and discuss the relation between dT_m/dP and the diffusivity of Li^+ ions in LMO.

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FIG. 1. (a) Schematic illustration of the crystal structure of LMO and (b) its oxygen sub-lattice along the [110] direction. LMO has a cubic spinel structure with a space group of $Fd\bar{3}m$, in which Li^+ ions occupy both tetrahedral $8a$ and octahedral $16d$ sites, while Mn ions sit the octahedral $16d$ site. The oxygen positional parameter (u) at 300 K is about 0.388 for the $x=0$ sample. The deviation from the ideal position $u=0.375$ leads to the distortion of the oxygen sub-lattice.

II. EXPERIMENTAL METHOD

Powder samples of LMO with $x=0, 0.05, 0.1, 0.15, 0.2$, and $1/3$ were prepared by a two-step solid-state reaction technique as reported previously.^{12,17} The reaction mixture of $\text{LiOH}\cdot\text{H}_2\text{O}$ and MnOOH was well mixed with a mortar and pestle, and pressed into a pellet of 23 mm diameter and ~ 5 mm thickness. The pellet was heated at 1273 K under air for 12 h, then crushed and repressed into a pellet again, and finally oxidized under air for 24 h at 973 K for $x=0$, 923 K for $x=0.05$, 873 K for $x=0.1$, 848 K for $x=0.15$, and 823 K for $x=0.2$. For $x=1/3$, the pellet was oxidized under air for 24 h at 923 K, 873 K, 823 K, and 773 K, successively, without cooling down to room T . The obtained powders were characterized by a powder X-ray diffraction (XRD) measurement at the synchrotron radiation facility of SPring-8, Japan and an inductively coupled plasma-atomic emission spectrometer (ICP-AES, CIROS 120, Rigaku Co., Ltd., Japan).

The electrochemical reactivity for LMO was examined in a non-aqueous lithium cell. In preparing the electrode, polyvinylidene fluoride (PVdF) dissolved in N-methyl-2-pyrrolidone (NMP) solution was used as a binder. The black viscous slurry consisting of 88 wt. % LMO powder, 6 wt. % acetylene black, and 6 wt. % PVdF was cast on an aluminum foil (ϕ 16 mm) with blade. The electrode was dried under vacuum at 393 K for 12 h in order to evaporate the NMP. Lithium metal pressed on a stainless steel plate (ϕ 19 mm) was used as a counter electrode. Two sheets of porous polyethylene membrane (TonenGeneral Sekiyu K. K., Japan) were used as a separator. The electrolyte was 1 M LiPF_6 dissolved in ethylene carbonate (EC)/dimethyl carbonate (DEC) (1/1 by volume ratio) solution (Kishida Chemical Co., Ltd., Japan). In order to obtain the steady-state voltammograms, the charge and discharge test for five cycles was first done in the voltage range between 3.0 and 4.2 V at constant current density of 0.15 mAcm^{-2} at 298 K. Then, cyclic voltammetry (CV) was carried out in the voltage range between 3.0 and 4.5 V at scan rate of $0.1 \text{ mV}\cdot\text{s}^{-1}$ (HZ-5000, Hokuto Denko Co., Ltd., Japan).

Weak-transverse-field (wTF-) μSR experiment was performed using high momentum muons on the μE1 decay muon beam line (GPD) at the Paul Scherrer Institut, Switzerland. The piston-cylinder-cell made of Cu-Be25 alloy [Fig. 2(a)] was used to apply P up to 1.4 and 2.8 GPa at room T . About six disks of the pressed sample [Fig. 2(b)] were stacked in the sample space (5.2 mm diameter and 20 mm height) of the cell. The 1:1 mixture of n -pentane and isoamyl

alcohols was used as a P medium in order to apply hydrostatic P to the sample. The actual P at low- T was monitored by the superconducting transition T of a piece of indium wire located at the bottom of the sample cell, by ac-susceptibility (χ) measurements, and then estimated to be 1.2 and 2.1 GPa. wTF- μSR spectra were recorded in the T range between 10 and 70 K with an applied magnetic field $H_{\text{wTF}} = 50$ G. The details of the experimental setup and techniques are described elsewhere.¹⁸

III. RESULTS

Figure 3 shows a typical example of the wTF- μSR spectra for the LMO sample with $x=0$ at $T=10$ and 70 K at $P=0.1$ MPa, in order to display a change in the muon asymmetry A_{wTF} with decreasing T . The wTF- μSR spectra for all the LMO samples were well fitted by a simple exponentially relaxing cosine function,

$$A_0 P(t) = A_{\text{wTF}} \exp(-\lambda_{\text{wTF}} t) \cos(\omega_\mu t + \varphi), \quad (1)$$

where A_0 is the initial muon decay asymmetry, $P(t)$ is the muon spin polarization function, A_{wTF} is the asymmetry from both sample and body of the HP cell, λ_{wTF} is the relaxation rate, ω_μ is the muon Larmor frequency, and φ is the initial phase of the muon precession. Although T_m for the LMO samples varies with x as illustrated later in Fig. 5(a), A_{wTF} decreases from ~ 0.25 ($=A_{\text{wTF}}^{\text{max}}$) at 70 K to ~ 0.2 ($=A_{\text{wTF}}^{\text{min}}$) at 10 K (Fig. 3). According to the previous μSR study on LMO using surface muon beam,^{11,12} the whole volume of the LMO sample was found to enter into a magnetic phase below T_m , for instance, $T_N = 61$ K for $x=0$, $T_f = 29$ K for $x=0.1$, and $T_f = 24$ K for $x=0.2$. Thus, the decrease in A_{wTF} by ~ 0.05 evidences a magnetic transition of the LMO samples.

Figure 4 shows the T dependence of the normalized wTF asymmetry (N_{ATF}) for the LMO samples with (a) $x=0$, (b) $x=0.1$, and (c) $x=0.2$ at $P=0.1$ MPa, 1.2 GPa, and 2.1 GPa. Here, $N_{\text{ATF}}(T)$ is calculated by

FIG. 2. (a) Piston cylindrical cell for high-pressure muon-spin rotation and relaxation measurements and (b) pressed $\text{Li}[\text{Li}_x\text{Mn}_{2-x}]\text{O}_4$ disks.

FIG. 3. wTF μ SR spectra for the $\text{Li}[\text{Li}_x\text{Mn}_{2-x}]\text{O}_4$ sample with $x=0.1$ at temperatures of 10 and 70 K at ambient pressure, $P=0.1$ MPa. The applied magnetic field H_{wTF} was 50 Oe. The muon asymmetry A_{wTF} consists of the asymmetry from both sample and body of the high-pressure cell.

FIG. 4. Temperature dependence of the normalized weak-transverse field asymmetry (N_{ATF}) for the $\text{Li}[\text{Li}_x\text{Mn}_{2-x}]\text{O}_4$ samples with (a) $x=0$, (b) $x=0.1$, and (c) $x=0.2$ at pressures (P) of 0.1 MPa, 1.2 GPa, and 2.1 GPa. The value of N_{ATF} was obtained by fitting the wTF- μ SR spectra with Eq. (1). T_m^{mid} was defined as temperature at which $N_{\text{ATF}}=0.5$. P dependence of T_m^{mid} is shown in the inset.

FIG. 5. x dependences of (a) magnetic transition temperature (T_m^{mid}) at pressures (P) of 0.1 MPa and 2.1 GPa, (b) slope of T_m^{mid} with P (dT_m^{mid}/dP), and (c) cubic lattice parameter (a_c) at $P=0.1$ MPa and 300 K in $\text{Li}[\text{Li}_x\text{Mn}_{2-x}]\text{O}_4$. The oxygen positional parameter (u) is also shown in (c).

$$N_{\text{ATF}}(T) = \frac{\{A_{\text{wTF}}(T) - A_{\text{wTF}}^{\text{min}}\}}{(A_{\text{wTF}}^{\text{max}} - A_{\text{wTF}}^{\text{min}})}, \quad (2)$$

and is roughly proportional to the volume fraction of paramagnetic (PM) phases in the sample. In other words, when $N_{\text{ATF}}=1$, the whole sample is in a PM state, while when $N_{\text{ATF}}=0$, the whole sample is in a magnetic phase, such as ferromagnetic, ferrimagnetic, AF, or spin-glass-like phase. As seen in Fig. 4(a), N_{ATF} for the $x=0$ sample at $P=0.1$ MPa starts to decrease from 1 at ~ 40 K and reaches 0 at ~ 25 K, indicating that the whole volume of the sample enters into the AF phase below 25 K. The magnetic transition temperature at which $N_{\text{ATF}}=0.5$ (T_m^{mid}) is 35.6(3) K. Note that T_m^{mid} for $x=0$ is ~ 25 K lower than the previous results on the $x=0$ compounds studied by neutron scattering¹⁰ and μ SR^{11,12} measurements. However, synchrotron XRD measurements for the present $x=0$ sample exhibit the structural phase transition from the high- T cubic ($Fd\bar{3}m$) phase to low- T orthorhombic ($Fddd$) phase at 285 K (not shown), which is a characteristic of stoichiometric LiMn_2O_4 .⁷ Also, as shown later in Fig. 6(a), a small cathodic peak around 3.3 V is clearly observed for the $x=0$ sample, confirming the stoichiometric Li/Mn ratio. Since T_N is very sensitive to x at the vicinity of $x=0$, the difference between the present T_m^{mid} and T_N is probably due to a small compositional difference of Li ions at the 16d site. In other words, magnetic measurements such as wTF- μ SR and neutron scattering are more sensitive

FIG. 6. Cyclic voltammogram of the Li/LMO cell with (a) $x=0$, (b) $x=0.05$, (c) $x=0.1$, and (d) $x=0.2$. Cyclic voltammetry was measured at scan rate of $0.1 \text{ mV} \cdot \text{s}^{-1}$ in the voltage range between 3.0 and 4.5 V. The LMO-electrode mix is fixed to $\sim 22 \text{ mg}$ for all the LMO cells in order to compare the values of the peak current at anodic direction (I_{pa}) and cathodic direction (I_{pc}). The x dependence of I_{pa} and I_{pc} is shown in (e).

to the stoichiometry of LiMn_2O_4 compared to XRD and electrochemical measurements.

As shown in Figs. 4(b) and 3(c), T_m^{mid} at $P=0.1 \text{ MPa}$ decreases with increasing x , that is, $T_m^{\text{mid}}=30.2(2) \text{ K}$ for $x=0.1$ and $T_m^{\text{mid}}=23.9 \text{ K}(2)$ for $x=0.2$. It is clearly found that T_m^{mid} for all the LMO samples increases with P ; the $N_{\text{ATF}}(T)$ curves simply shift towards the higher T side. Furthermore, a linear relationship between T_m^{mid} and P is found up to 2.1 GPa (see the insets in Fig. 4).

Figure 5(a) shows the T_m^{mid} obtained at $P=0.1 \text{ MPa}$ and 2.1 GPa as a function of x in LMO. T_m^{mid} decreases with increasing x regardless of P , but the slope (dT_m^{mid}/dP) around $x=0.1$ seems to be larger than those for other LMO samples. Indeed, as illustrated in Fig. 5(b), dT_m^{mid}/dP has the maximum at $x=0.1$, i.e., as x increases from 0, dT_m^{mid}/dP rapidly increases from $0.9(1) \text{ K/GPa}$ to $1.4(1) \text{ K/GPa}$ at $x=0.1$, then drops to $0.7(1) \text{ K/GPa}$ at $x=0.15$, and finally approaches almost constant value ($\sim 0.4 \text{ K/GPa}$) with further increasing x . Although there has been few reports on the HP- μSR studies for other spinel oxides, the dT_m^{mid}/dP value for LMO is about 30%–50% to that for Co_3O_4 ($\sim 2.2 \text{ K/GPa}$),¹⁹

where the ionic distribution of Co_3O_4 is represented as $(\text{Co}^{2+})_{8a}(\text{Co}^{3+})_{16d}\text{O}_4$.

In order to clarify the interrelationship between electrochemical properties and x for LMO, Fig. 6 shows the cyclic voltammogram of the Li/Li[Li_xMn_{2-x}]O₄ cell with (a) $x=0$, (b) $x=0.05$, (c) $x=0.1$, and (d) $x=0.2$. For the $x=0$ sample, two anodic peaks are observed around 4.10 and 4.21 V. The former corresponds to the one-phase reaction in the y range between 0 and ~ 0.5 in $\text{Li}_{1-y}\text{Mn}_2\text{O}_4$, while the latter corresponds to the two-phase reaction below $y=0.5$.² As described above, the small cathodic peak around 3.3 V correlates with the disappearance of a “double hexagonal” phase in $\text{Li}_{1-y}\text{Mn}_2\text{O}_4$,¹ which is a characteristic of stoichiometric LiMn_2O_4 . As x increases from 0, two anodic (or cathodic) peaks gradually change to a broad single peak, suggesting the one-phase reaction in the whole y range in $\text{Li}_{1-y}[\text{Li}_x\text{Mn}_{2-x}]\text{O}_4$ ($y=1-3x$). Figure 6(e) shows the peak current at anodic direction (I_{pa}) and cathodic direction (I_{pc}) as a function of x in LMO. Both $I_{pa}(x)$ and $I_{pc}(x)$ curves exhibit the maximum at $x=0.1$ as in the case for the x dependence of dT_m^{mid}/dP [Fig. 5(b)]. In a reversible electrode, a peak current (I_p) in the cyclic voltammogram is related with the diffusion coefficient (D) by²⁰

$$I_p = 0.4463 \left(\frac{F^3}{RT} \right)^{1/2} n^{3/2} A D^{1/2} C v^{1/2}, \quad (3)$$

where F is the Faraday constant, R is the gas constant, T is the absolute temperature, n is the number of electrons involved in an electrode reaction, A is the reaction surface area, C is the bulk concentration, and v is the scan rate. Since the weight of positive electrode is uniformed to be $\sim 22 \text{ mg}$ for all the LMO cells, the diffusivity of Li^+ ions (D_{Li}) is thought to have a maximum at $x=0.1$.

IV. DISCUSSION

A. x dependence of dT_m^{mid}/dP

As seen in Figs. 4 and 5(a), T_m^{mid} increases with P in the whole x range. It should be noted that at ambient P , the O-Mn-O bond angles do not change with x , but the distance between Mn ions ($d_{\text{Mn-Mn}}$) decreases almost linearly with x . This is because a_c , at $P=0.1 \text{ MPa}$ and $T=300 \text{ K}$, decreases monotonically with x , whereas u remains almost constant (~ 0.387) in the whole x range [Fig. 5(c)]. Although we have no data for the change in a_c with P in the low- T , according to the previous results for a structural analysis of LiMn_2O_4 as a function of P , a_c at 350 K decreases monotonically with a slope $(da_c/dP) \sim 0.01 \text{ \AA/GPa}$ up to $\sim 2 \text{ GPa}$.²¹ In addition, XRD and Raman studies under P on the other spinel oxides such as NiMn_2O_4 ,²² ZnFe_2O_4 ,²³ and Zn_2TiO_4 ²⁴ suggest that a_c linearly decreases with P , while u is independent of P . Therefore, the positive P dependence of T_m^{mid} for LMO is likely to be attributed to the decrease in $d_{\text{Mn-Mn}}$. That is, since the MnO_6 octahedra are compressed by P , the crystal electric field is enhanced by P , leading to larger splitting of the $3d$ orbitals than that at $P=0.1 \text{ MPa}$.

In contrast to the linear relationship between x and T_m^{mid} at $P=0.1 \text{ MPa}$, a broad maximum in the $dT_m^{\text{mid}}/dP(x)$ curve

indicates that at least two opposite effects contribute to determine T_m^{mid} under P [Figs. 5(a) and 5(b)]. If we assume that the decrease in $d_{\text{Mn-Mn}}$ governs T_m^{mid} under P , the $dT_m^{\text{mid}}/dP(x)$ curve suggests that the change in $d_{\text{Mn-Mn}}$ under P is the largest at the $x=0.1$ composition, namely, the $x=0.1$ sample is the softest in the whole x range. Although the origin of P dependence on $d_{\text{Mn-Mn}}$ (or T_m^{mid}) is currently unclear, the decrease in a_c with x naturally inhibits the decrease in $d_{\text{Mn-Mn}}$ under P . On the other hand, the cooperative JT distortion disappears with x , although our μSR studies on LMO clarifies that a short-range cooperative JT distortion exists even at the $x=0.15$ composition.¹¹ Since the $\text{Mn}^{3+}\text{-Mn}^{3+}$ and $\text{Mn}^{4+}\text{-Mn}^{4+}$ ions are strongly bound in the cooperative JT distortion phase, the increase in x would release the couplings between Mn^{3+} (or Mn^{4+}) ions. This consideration is consistent with our recent XRD studies on LMOs; as x increases from 0, the thermal expansion coefficient, which correlates the bond strength between Mn ions, slightly increases up to $x=0.1$, then levels off with further increasing x .²⁵

B. Correlation between dT_m^{mid}/dP and D_{Li}

Considering the crystal structure of LMO (see Fig. 1), only the Li^+ ions at the $8a$ site seem to participate the electrochemical reaction of $\text{Li}_{1-y}[\text{Li}_x\text{Mn}_{2-x}]\text{O}_4$ ($y=1-3x$) in the y range between 0 and 1. Actually, the observed capacity in the voltage range between 3.0 and 4.2 V at low current density of 0.15 mA cm^{-2} decreases with increasing x . However, CV demonstrates that the $I_{\text{pa}}(x)$ [$I_{\text{pc}}(x)$] curve, in other words, the $D_{\text{Li}}(x)$ curve shows the maximum at $x=0.1$ (Fig. 6). This means that the Li^+ ions at the $16d$ site play a significant role on the electrochemical kinetics of LMO. Here, it has been established that the local compositional inhomogeneities during solid-state diffusion generate stresses, leading to particle level fracture, degradation of rate capability, and capacity fading of LIB.²⁶⁻³¹ This is called as diffusion-induced stress (DIS) and should be minimized in order to increase the rate capability and mechanical durability. The x dependence of dT_m^{mid}/dP implies that the $x=0.1$ sample is softest in the whole x range. Since the simulation studies on DIS²⁶⁻³¹ suggest that the soft and flexible materials have better rate capability rather than hard and brittle ones, the soft material nature of the $x=0.1$ sample would decrease the DIS during Li extraction and insertion. In other words, the x dependence of dT_m^{mid}/dP is thought to be correlates with that of D_{Li} .

Finally, we wish to emphasize the unique spatial resolution of μSR technique. In contrast to dc- χ measurements, muon reflects the magnetic fields within a few angstrom, and consequently, it is very sensitive to microscopic magnetism and crystal structure.¹³ Positive muon is most likely to bind to the nearest O^{2-} ion with a typical bond length $d_{\mu-\text{O}} = 1 \text{ \AA}$,¹³ which feels the nuclear magnetism of Li ions at the $8a$ site [Fig. 1(b)]. Most of the LIB materials except for Li_xCoO_2 enter into a magnetic phase below $\sim 100 \text{ K}$.^{11,12,32,33} Thus, HP- μSR study provides microscopic information concerning DIS, although a change in volume during extraction and insertion is currently used for simulating the DIS of LIB materials.²⁶

V. CONCLUSION

We have found an abnormal the pressure (P) dependence of the magnetic transition temperature (T_m^{mid}) for (LMO) by μSR measurements. That is, although T_m^{mid} at ambient P monotonically decreases with increasing x , a slope of the T_m^{mid} vs. P shows the maximum at $x=0.1$. Since cyclic voltammetry also demonstrates the highest diffusivity of Li^+ ions at $x=0.1$, the Li^+ ions at the $16d$ site, in other words, soft and flexible nature plays an essential role for determining an electrochemical kinetics of LMO. We expect that high-pressure μSR studies are applicable for studying a diffusion-induced stress of lithium-ion battery materials.

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