Determination of the nature of fluctuations using $^8$Li and $^9$Li $\beta$-NMR and spin-lattice relaxation.

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We report a comparison of the $1/T_1$ spin lattice relaxation rates (SLR) for $^9$Li and $^8$Li in Pt and SrTiO$_3$, in order to differentiate between magnetic and electric quadrupolar relaxation mechanisms. In Pt, the ratio of the $1/T_1$ spin relaxation rates $R_{\text{p}}$, was found to be 6.82(29), which is close to but less than the theoretical limit of $\sim 7.68$ for pure magnetic relaxation. In SrTiO$_3$ this ratio was found to be 2.7(3), which is close but larger than the theoretical limit of $\sim 2.14$ expected for pure electric quadrupolar relaxation. These results bring new insight into the nature of the fluctuations in the local environment of implanted $^8$Li observed by $\beta$-NMR.

I. INTRODUCTION

$^8$Li $\beta$-detected NMR ($\beta$-NMR) has been established as a powerful tool for material science due to its inherent sensitivity to magnetic and electronic properties. The principal success of TRIUMF’s low-energy incarnation of $\beta$-NMR is the ability to study thin films, surfaces, and interfaces — where conventional NMR is difficult or impossible. This stems from $\beta$-NMR’s high sensitivity relative to conventional NMR; for $\beta$-NMR typically only $\sim 10^9$ nuclei (instead of $\sim 10^{17}$) are required for a signal. The only other real-space technique with equivalent sensitivity over a comparable material length scale (viz. 10 nm to 200 nm) is low-energy $\mu$SR (LE-$\mu$SR); however, it operates in a complementary time-window due to the different probe lifetimes ($1.21 \text{ s for } ^8\text{Li}^+ \text{ vs. } 2.2 \mu\text{s for } ^6\mu^+$). Thus, both techniques have leveraged the nuclear physics of beta decay to investigate topical problems in condensed matter physics including magnetic surfaces, thin film heterostructures, topological insulators, superconductors etc.

A key issue in any $^8$Li $\beta$-NMR experiment is to identify the source of spin-lattice relaxation (SLR) and in particular whether the fluctuations driving the SLR are magnetic or electric in origin. Unlike the positive muon, $\mu^+ (I = 1/2)$, $^8\text{Li} (I = 2)$ is not a pure magnetic probe and its relaxation is sensitive to both fluctuating magnetic fields and electric field gradients (EFG’s). In some cases, the primary source of relaxation may be inferred. For example, in simple metals the observed relaxation is linear in temperature as expected from the Korringa relaxation, which originates from a magnetic hyperfine interaction between the nuclear spin and the spin of the conduction electrons. However, in more complicated instances, such as heterostructures comprised of magnetic and non-magnetic layers, it becomes difficult to determine the contribution of each type of relaxation. LaAlO$_3$/SrTiO$_3$ multilayers are particularly illustrative of this point; the bulk layers are non-magnetic insulators, while there is evidence of magnetism at their interfaces.

In conventional NMR it is possible to differentiate between relaxation mechanisms by isotopic variation of the nuclear probe, since the absolute relaxation rates for each isotope scale according to their nuclear moments. For two isotopes with significantly different nuclear moments (e.g., $^6$Li and $^7$Li) the ratio of the relaxation rates should be distinctly different in the limits of either pure magnetic or pure electric quadrupolar relaxation. In this study we test the feasibility of isotope comparison applied to $\beta$-NMR — using $^8$Li and $^9$Li, two $\beta$-radioactive isotopes. The stopping sites of $^8$Li and $^9$Li are often interstitial rather than substitutional as in the case of conventional NMR. However, we expect that both implanted $^6$Li and $^9$Li will probe the same sites. Measurements on $^6$Li are more time consuming than those for $^8$Li. This is related to the fact that $^6$Li lies one neutron further away from the valley of stability, consequently the beam intensity in this experiment was about 10 times lower for $^9$Li than $^8$Li, and has a more complicated $\beta$-decay scheme, which results into a beta-decay asymmetry for $^9$Li about 3 times smaller than for $^8$Li, as will be discussed below.

Measurements reported here were made in Pt metal, where the spin relaxation rate of $^8$Li (9Li) is dominated by Körnringa scattering, which is magnetic, and in strontium titanate (SrTiO$_3$), which is a non-magnetic insulator with a large static electric quadrupolar interaction for implanted $^8$Li. SrTiO$_3$ is a common substrate material but also has interesting properties on its own which have been studied extensively with a wide variety of methods including $\beta$-NMR. Although we expect the quadrupolar fluctuations in EFG causing spin relaxation to dominate, there are also potential magnetic sources of relaxation that could contribute as explained below.

In the following sections we first summarize the theoretical considerations behind $\beta$-NMR, as well as the isotopic variation method. This is then followed by a description of the experiment and finally we present the experimental results along with a discussion.

II. THEORY

The basis of $\beta$-NMR is the parity-violating weak interaction, whereby the direction of the emitted electron (positron) from the decaying nucleus is correlated with the nuclear spin...
polarization at the time of decay:

\[ W(\theta) = 1 + \beta a p \cos(\theta) \] (1)

where \( \beta = v/c \) is the velocity of the high energy electron (positron) normalized to the speed of light, \( p \) is the magnitude of the nuclear polarization vector, \( \theta \) is the angle between the nuclear polarization and the electron (positron) velocity and \( a \) is the asymmetry parameter depending on the properties of nuclear \( \beta \)-decay. The theory of nuclear beta-decay predicts that \( a \) is about 1/3 for \(^9\text{Li}\) and considerably smaller (\(~0.1\)) for \(^8\text{Li}\)\(^{11}\), if averaged over all the decay modes.

The reduction in asymmetry for \(^9\text{Li}\) compared to \(^8\text{Li}\) is attributed to \(^8\text{Li}\)‘s more complicated \( \beta \)-decay scheme. In particular, \(^8\text{Li}\) has three main decay channels, two of which have opposite asymmetries that nearly cancel after weighting by the branching probabilities. Thus, most of the observed asymmetry is from the weakest decay mode which has a branching probability of only 0.1 but a large theoretical asymmetry parameter \( a \approx 1.0 \). The relevant branching probabilities and asymmetries of each decay mode are reported in Fig. 1. We note in passing that it should be possible to enhance the \( \beta \)-NMR signal from \(^9\text{Li}\) by tagging events according to whether an \( \alpha \) is emitted or not, which will allow us to distinguish between the different decay channels and isolate their contributions. This is currently being explored as a way to optimize the \( \beta \)-NMR of \(^9\text{Li}\).

The resulting anisotropic decay pattern for the high energy electron (positron) allows one to monitor the nuclear polarization from highly polarized \(^9\text{Li}^+\) or \(^9\text{Li}^+\) beams implanted in the sample. In particular, the asymmetry in the count rate at time \( t \) between two opposing beta detectors is proportional to the component of nuclear polarization along the direction defined by the two detectors:

\[ A(t) = \frac{N_B(t) - N_F(t)}{N_B(t) + N_F(t)} = A_0 p_z(t) \] (2)

where \( N_B(t) \) and \( N_F(t) \) are the counts measured in the backward and forward detectors, \( p_z(t) \) is the component of nuclear polarization along the \( z \)-axis defined by the detectors, and \( t \) is the time of decay after implantation. The detectors are generally positioned so that \( z \) is along the direction of initial polarization. Note that the asymmetry in the count rate has a maximum value of \( A_0 \) at \( t = 0 \) which is reduced relative to the theoretical asymmetry \( a \), as calculated from the nuclear properties, owing to instrumental effects such as the finite solid angle subtended by the detectors and scattering of the betas before reaching the detectors. Note also that \( p_z(t) \) and thus \( A(t) \), are time dependent, reflecting the fact that the nuclear polarization is subject to spin relaxation processes in the sample, which in fact is the quantity of interest in this experiment.

Information on the fluctuations of the electromagnetic fields in a material of interest is obtained through measurements of the spin-lattice relaxation (SLR) rate in the absence of a RF magnetic field. The SLR may be studied by implanting a series of beam pulses into the sample and then monitoring \( \mathcal{A}(t) \), which is the convolution of \( A(t-t') \) with the beam pulse \( N(t') \) where \( t' \) is the time of arrival for given probe and \( t-t' \) is the time spent in the sample before its beta decay:

\[ \mathcal{A}(t) = \int_{-\infty}^{t} N(t') A(t-t')dt' \] (3)

In general the SLR rate, usually denoted as \( 1/T_1 \) (with \( T_1 \) being the longitudinal spin-lattice relaxation time), originates from fluctuations in the local environment arising from fundamental processes such as phonon scattering, magnon scattering, conduction electron scattering, diffusion, etc. The total observed rate can be decomposed into a sum of individual contributions, which may be grouped into magnetic (\( 1/T_1^M \)) and electric quadrupolar (\( 1/T_1^Q \)) terms:

\[ \frac{1}{T_1} = \frac{1}{T_1^M} + \frac{1}{T_1^Q} \] (4)

Most often one of the relaxation mechanisms will dominate. For instance, we expect Korringa relaxation to be dominant in simple metals.

The magnitudes of each contribution for a given probe nucleus scale according to their nuclear properties; namely, their spin, \( I \), magnetic moment, \( \mu \), and electric quadrupole moment, \( Q \). Measurements of SLR rates for two different isotopes under identical experimental conditions (i.e., magnetic field, temperature, etc.) can be compared through their ratio, \( R \):

\[ R(I,I') = \frac{1/T_1(I)}{1/T_1(I')}, \quad \frac{1}{1/T_1^M(I)} + \frac{1}{1/T_1^Q(I)} = \frac{1}{1/T_1^M(I')} + \frac{1}{1/T_1^Q(I')} \] (5)

where \( I \) and \( I' \) denote the spin quantum number of each isotope. Two limits are of interest here: when the relaxation is solely due to either magnetic or quadrupolar interactions within the host-sample. In the former case, Eq. (5) reduces to the ratio of pure magnetic relaxation, \( R_{M} \), which in the limit of fast fluctuations (i.e., \( \tau^{-1} \gg \tau_0 \), where \( \tau_0 \) is the NMR correlation time and \( \omega_0 \) is the Larmor resonance frequency) is:

\[ R_{M}(I,I') = \left( \frac{\mu/I}{\mu'/I'} \right)^2 = \left( \frac{\gamma}{\gamma'} \right)^2 \] (6)
where $\mu$ and $\gamma$ are the magnetic moment and gyromagnetic ratio of each isotope. Note that the fast fluctuation limit ensures that $1/T_1$ is independent of $\omega_0$.

In the other case, Eq. (5) yields the ratio of relaxation rates in the pure quadrupolar limit, $R_Q$:

$$R_Q(I, I') = \frac{f(I)}{f(I')} \left( \frac{Q}{Q'} \right)^2,$$  

(7)

where $Q$ are the nuclear quadrupole moments, and

$$f(I) = \frac{2I + 3}{I^2(2I - 1)}.$$  

(8)

Thus, given the nuclear moments of each isotope, one can calculate the ratio of relaxation rates when either mechanism is dominant. Using Eqs. (6) and (7), along with the nuclear spins and moments for $^{6}$Li and $^{7}$Li (see Table I), we find the limiting cases for $T_1^{-1}(^{6}$Li)/$T_1^{-1}(^{7}$Li): 7.67964(16) and 2.1362(4) for $R_M$ and $R_Q$, respectively. The difference between these limits is not as pronounced as for $^{6}$Li and $^{7}$Li, where $R_M$ and $R_Q$ differ by a factor of $\sim 90$. Nevertheless, $^{6}$Li and $^{7}$Li are sufficiently different that the nature of fluctuations and resulting spin relaxation (magnetic versus electric quadrupolar) may be differentiated by such a comparison.

### III. EXPERIMENTAL

The experiment was performed using 18 keV beams of $^{8}$Li$^+$ and $^{9}$Li$^+$ at TRIUMF’s Isotope Separator and Accelerator Facility (ISAC) in Vancouver, Canada. ISAC is capable of providing an intense beam for a large number of isotopes of various elements, including $^{6}$Li and $^{7}$Li. For this experiment, TRIUMF’s dedicated $\beta$-NMR and $\beta$-NQR spectrometers were used. A detailed discussion on the characteristics of the spectrometers can be found elsewhere.

Before reaching the spectrometer, the Li$^+$ ion beam first passes through the ISAC polarizer. The first stage of the polarizer is to neutralize the beam by passing it through a Rb vapor cell. The neutral beam then drifts $\sim 2$ m during which time the $2S_{1/2} \rightarrow 2P_{1/2}$ optical $D_1$ transition is pumped with circularly polarized laser light. The last stage is to re-ionize the beam in a He gas so that the polarized beam can be delivered alternately to the spectrometers. Previous work shows that the nuclear polarization of the beam after stopping in the sample is $\sim 70\%$.

It is important to note that unlike conventional NMR, where the Boltzmann factor determines the polarization, the nuclear polarization in $\beta$-NMR is close to unity and independent of the sample temperature and magnetic field. Consequently, measurements can be made under conditions where conventional NMR is difficult or impossible e.g. at high temperatures, low magnetic fields or in thin films. The intensity of the implanted beam (typically $\sim 10^7$ s$^{-1}$), is such that the concentration of the nuclear probes is so small that there is no interaction between probes and thus no homonuclear spin-coupling.

### IV. RESULTS AND DISCUSSION

To demonstrate the comparison of $^{8}$Li and $^{9}$Li in $\beta$-NMR, two very different materials were selected. The first is Pt which is a d-band metal in which the $^{6}$Li resides at a site with little or no quadrupolar interaction. In this test case we expect the relaxation to be predominantly magnetic, originating from Korringa scattering. SrTiO$_3$ on the other hand is a non-magnetic insulator with few nuclear moments. Previous work in SrTiO$_3$ shows that $^{7}$Li experiences a large quasistatic quadrupolar interaction. Thus in this case we expect quadrupole fluctuations to play a more important role. Nevertheless, it is still unclear to what extent magnetic effects can be neglected in SrTiO$_3$. For example, it is well known that the implantation of $^{7}$Li generates vacancy-interstitial pairs as well as electron-hole pairs. Such defects are often magnetic. For example O vacancies in SrTiO$_3$ result in two Ti$^{3+}$ ions which are typically paramagnetic. In principle, the resulting paramagnetic defects would have low frequency magnetic fluctuations which will contribute to the SLR of the implanted Li nucleus in SrTiO$_3$.

#### A. Platinum

$^{8}$Li$^+$ resonance measurements in Pt have shown a single narrow line below 300 K, indicating that $^{8}$Li$^+$ occupies a single site with a vanishing (static) EFG. The spectrum is also simpler than in other metals, where multiple Li$^+$ sites are found below 300 K.

Given the simplicity of the resonance spectrum we expect SLR in Pt to follow a single exponential form with:

$$A(t - t') = \exp \left[ -\lambda (t - t') / T_1 \right],$$  

(9)

Substituting this into Eq. (3) and assuming a square beam pulse during the time interval $[0, \Delta]$, one obtains a form for the asymmetry during and after the pulse given by:

$$\mathcal{A}(t) = \begin{cases} 
A_0 \exp\left[-\tau_0 (t - t')/T_1\right], & t \leq \Delta \\
A(\Delta) \exp\left[-(t - \Delta)/T_1\right], & t > \Delta,
\end{cases}$$  

(10)

where $\tau_0$ is the radioactive lifetime, $1/\tau' = 1/\tau_0 + 1/T_1$ and $A_0$ is the initial asymmetry at the time of implantation. Note that the SLR spectrum has two distinct regions (see Fig. 2): during the beam pulse ($0 < t < \Delta$) the asymmetry relaxes towards a dynamic equilibrium value:

$$\mathcal{A} = \frac{A_0}{1 + \tau_0/T_1},$$  

(11)

whereas after the beam pulse ($t > \Delta$) $\mathcal{A}(t)$ decays towards the Boltzman equilibrium value, which is essentially zero on our scale. Note the pronounced kink in $\mathcal{A}(t)$ at $t = \Delta$ when the beam pulse ends. This is also the time with the highest event rate and smallest statistical uncertainty in $\mathcal{A}(t)$. For both isotopes the length of the beam pulse ($\sim 3.3\tau_0$) and the total observation time ($\sim 9.9\tau_0$) were chosen to minimize the statistical uncertainties.
TABLE I. Intrinsic nuclear properties of Li radioisotopes used in $\beta$-NMR and $\beta$-NQR. $I^\pi$ is the nuclear spin (and parity), $\mu$ is the magnetic moment, and $Q$ is the electric quadrupole moment.

| Isotope | $I^\pi$ | $\tau_N$ (s) | $\mu$ (µN)$^a$ | $Q$ (mb)$^b$ |
|---------|---------|--------------|----------------|--------------|
| $^7$Li  | $2^+$   | $1.2096(5)^{14}$ | $+1.65356(18)^{13}$ | $+32.6(5)^{16}$ |
| $^9$Li  | $3/2^-$ | $0.2572(6)^{17}$ | $+3.43678(6)^{15}$ | $-31.5(5)^{16}$ |

$^a$ The magnetic moments have been corrected for diamagnetic shielding.
$^b$ The quadrupole moments were determined from their ratios, starting with the well-known value for $^7$Li$^{13}$.

The SLR rates for $^8$Li$^+$ and $^9$Li$^+$ implanted at an energy of 18 keV at 300 K were measured in magnetic fields of 1.90 T and 6.55 T — the latter shown in Fig. 2. Several general distinctions should be pointed out between SLR spectra for $^8$Li$^+$ and $^9$Li$^+$ in Pt: The initial asymmetry (i.e., $A_0$) for $^8$Li$^+$ is $\sim$6 times greater than for $^9$Li$^+$; $1/T_1$ is $\sim$7 times larger for $^9$Li$^+$ than for $^8$Li$^+$; and the relative uncertainty of the SLR rate measurements for $^9$Li$^+$ is greater by a factor of $\sim$5 than for $^8$Li$^+$. The latter can be understood as follows: The statistical figure of merit for any $\beta$-NMR measurement is $A^2N$, where $A$ is the observable asymmetry and $N$ is the total number of decay events — both factors for $^9$Li are significantly reduced relative to $^8$Li. Since $^9$Li lies further away from the valley of nuclear stability, it has a shorter half-life and fewer ions are extracted from the ion source and delivered to the spectrometer (here $\sim10^6$ s$^{-1}$ vs $\sim10^3$ s$^{-1}$ for $^8$Li$^+$). This in turn reduces the factor $N$ for $^9$Li. Also, as explained above, the asymmetry for $^9$Li is much smaller than for $^8$Li. As a result, about 90% of the data acquisition was spent on $^9$Li, since these results dominated our uncertainty in the ratio of the relaxation rates.

Temperature dependent SLR of $^8$Li$^+$ in Pt has been studied previously by Ofer et al. between 3 K to 295 K at 4.10 T, where the SLR rate was found to increase linearly with temperature, implying Korringa relaxation$^7$. This relation holds for high magnetic fields and different implantation energies. The temperature-dependent $^{8}$Li$^+$ SLR rates at various magnetic fields are shown in Fig. 3, including our measurements, as well as results on Pt foil by Ofer et al.. The $^8$Li SLR rate at 6.55 T is in good agreement with the Korringa fit by Ofer et al., extrapolated to 300 K, whereas the measured SLR rate at 1.9 T is lower by about 10%. It is unlikely that this is a real effect since any additional source of relaxation would increase the relaxation at the lower magnetic field which is opposite to what is observed. The slight reduction in $1/T_1$ measured at 1.9 T suggests there may be a small systematic error related to the fact that the beam spot is a bit larger and the ratio between the beta rates in the two detectors is different compared to the higher field. However, it should be noted that the measured $^8$Li SLR rates in Pt foil appear to increase linearly with temperature, independent of implantation energy and applied magnetic field.

The ratios of $T_1^{-1}(^{8}$Li$)/T_1^{-1}(^{7}$Li$)$ at 6.55 T and 1.90 T are in good agreement with each other and we find a relaxation rate ratio, $R_{Pt}$, of 6.8(4) and 5.9(9) at 6.55 T and 1.90 T, re-
The solid line is Korringa fit to the data. It has been studied extensively with a (100) cubic crystallographic axis. It is evident from the data that the relaxation is more complex than in Pt since a single exponential fails to describe the decay of spin polarization. One might expect this since a magnetic field applied along the (100) direction breaks the local symmetry between the three otherwise equivalent sites. More specifically the EFG tensor is axially symmetric about one of the three orthogonal cubic axes. Thus the applied magnetic field is either along EFG axis or perpendicular to it. However the relaxing fraction, $f$, was approximately field-independent, within our range of fields including the spectrum at zero field. The solid line is Korringa fit to all the SLR rates in Pt and differs somewhat from the result of Ofer et al.

due to the additional data points from this work.

**B. Strontium Titanate**

SrTiO$_3$ was chosen as a second example, since it is a non-magnetic insulator and representative of a material where the relaxation in $^8$Li $\beta$-NMR is expected to be dominated by quadrupolar fluctuations. It has been studied extensively with low-energy $^8$Li $\beta$-NMR. Implant $^8$Li occupies a single non-cubic site, which is unambiguously evidenced by the observation of a pure nuclear quadrupole resonance (NQR) in zero magnetic field.

Figure 4 shows the SLR spectra for $^8$Li and $^9$Li at 300 K at various magnetic fields between 0 mT to 15 mT applied along a (100) cubic crystallographic axis. It is evident from the data that the relaxation is more complex than in Pt since a single exponential fails to describe the decay of spin polarization. One might expect this since a magnetic field applied along the (100) direction breaks the local symmetry between the three otherwise equivalent sites. More specifically the EFG tensor is axially symmetric about one of the three orthogonal cubic axes. Thus the applied magnetic field is either along EFG axis or perpendicular to it. However the relaxing fraction, $f$, was approximately field-independent, within our range of fields including the spectrum at zero field. The solid line is Korringa fit to all the SLR rates in Pt and differs somewhat from the result of Ofer et al.

due to the additional data points from this work.

**C. Ratio of relaxation rates**

The ratio of relaxation rates in platinum $R_{Pt} = 6.82(29)$, which is the weighted average of the measurements at 6.55 T and 1.90 T. Note that this value is somewhat less than expected from the pure magnetic limit $R_M$ (Fig. 6).

The reason for this discrepancy is puzzling. All measurements were taken at 300 K where the lithium ions could have some quadrupolar contribution due to local vibrations and scattering of phonons which leads to a fluctuating EFG. However $1/T_1$ is very linear in temperature, whereas any such contributions would have a stronger temperature dependence. It would be interesting to repeat the measurements at a lower temperature to check if $R_{Pt}$ is closer to the magnetic limit or not. In principle the scattering of electrons at the Fermi surface, which is responsible for Korringa relaxation (see Fig. 3), could also produce a fluctuating EFG and a linear temperature dependence $1/T_1$, which is electric quadrupolar in origin. However, we could not find any calculations of this effect. In any case, an electric quadrupolar contribution to $1/T_1$ cannot be very large in Pt at 300 K.
FIG. 4. SLR spectra of $^8\text{Li}$ (left) and $^9\text{Li}$ (right) in single crystal SrTiO$_3$ at 300 K. The solid lines are a global fit to Eqs. (3) and (12) where a common parameter $f$ is shared between all spectra.

FIG. 5. Field dependence of $1/T_1$ for $^8\text{Li}$ and $^9\text{Li}$ in SrTiO$_3$ at 300 K. The (orange) triangle represents a linear interpolation at 3.6 mT from the 2.5 mT and 5 mT $^8\text{Li}$ measurements.

We also reported a value of $R_{STO}$ in two samples of SrTiO$_3$. In the first sample, the weighted average $R_{STO}$ of the measurements at 3.6 mT and 10 mT yielded 2.9(4). This value is close, but not within experimental error of the quadrupolar limit of $R_Q \approx 2.14$. After taking into account the measurement on the second SrTiO$_3$ sample, which was 2.4(5) at 10 mT, the weighted ratio of relaxation rates in SrTiO$_3$ is found to be 2.7(3), closer to the quadrupolar limit. Still there is a small disagreement which suggests some small magnetic contribution to $1/T_1$. This may be related to the observed non-exponential relaxation function. If it is due to fluctuations which are inhomogeneous in time or space then nearby defects are likely playing some small role. A small portion of these fluctuations could be magnetic in origin. For example any O vacancies a few lattice sites away would give rise to paramagnetic Ti$^{3+}$ ions. Similarly electron-hole pairs in a triplet state would also be magnetic.

FIG. 6. Ratios of $^9\text{Li}$ to $^8\text{Li}$ $1/T_1$ relaxation rates in Pt (weighted average of all measurements) and in the two SrTiO$_3$ samples. The red line represents the weighted average of the measurements in both SrTiO$_3$ samples.
V. CONCLUSIONS

We have measured the ratio between $1/T_1$ of $^9$Li and $^8$Li in Pt and SrTiO$_3$ in order to help identify the nature of the fluctuations responsible for the spin relaxation (i.e., if they are magnetic or electric quadrupolar). In Pt, the relaxation is single exponential and the ratio $R_T$ was found to be very close to but slightly less than the pure magnetic limit. This is consistent with Korringa relaxation being dominant as suggested by the linear temperature dependence in $1/T_1$ reported previously. Nevertheless, the small reduction in $R_T$ relative to the pure magnetic limit means that excitations causing a fluctuating EFG may provide a small contribution to the observed spin relaxation. Further measurements at lower temperatures would be needed to verify this.

In SrTiO$_3$ at 300 K the results confirm that the dominant source of relaxation is electric quadrupolar. However, the relaxation function is more complicated involving a relaxing source of relaxation is electric quadrupolar. However, the relaxation function is more complicated involving a relaxing source of relaxation.

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This sample was SrTiO$_3$ with 30 nm LaTiO$_3$ capping layer. Bulk LaTiO$_3$ is a prototypical Mott insulator and is antiferromagnetic below $\sim$135 K. Like SrTiO$_3$, LaTiO$_3$ is non-magnetic at 300 K, though transport measurements have shown the existence of a metallic and superconducting heterointerface; however, at an implantation energy of 18 keV, only a negligible fraction of the probing ions stops in the LaTiO$_3$ film, or near the interface. This was confirmed for both $^6$Li and $^9$Li by using the Monte Carlo-based simulation package SRIM 2008. For this reason, this can be considered to be effectively an SLR measurement in the SrTiO$_3$ substrate of the film.