Low-energy $\mu$SR study on the tetradymite topological insulator $\text{Bi}_{1.5}\text{Sb}_{0.5}\text{TeSe}_2$

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Abstract

A new method utilizing the low energy muon spin rotation ($\mu$SR) technique to investigate the spin structure within the surface layer of topological insulator has been proposed. In order to detect the spin polarization parallel with the surface, one applies a weak field $B_{\text{par}}$, which, by breaking the time reversal symmetry, is expected to induce a net magnetization perpendicular the surface. This will affect the profile of muon spin depolarization spectra. Preliminary measurements on the topological insulator $\text{Bi}_{1.5}\text{Sb}_{0.5}\text{TeSe}_2$ with tetradymite structure are also shown.

Keywords: Topological insulator, spin-locking, muSR

1 Introduction

The non-trivialness of a topological insulator is distinguished from an ordinary insulator by the presence of a gapless surface state, which is topologically protected and robust against disorder. The surface state of three dimensional topological insulators is characterized by a Dirac-cone dispersion which has been shown to have a helical spin structure, where the spin vector points parallel to the surface and perpendicular to the momentum (“spin-locking”) [1-3]. We propose a new method to investigate this spin-locking in the surface layer by utilizing $\mu$SR technique. Due to the Kramers degeneracy in the surface current, no hyperfine field is expected, and hence the state is not likely to be detected by muons. This can be overcome simply by an application of field $B_{\text{par}}$, which breaks the time reversal symmetry. The space inversion symmetry is also broken at the sample surface, and both the up and down spins lean to either inward or outward of the sample, and hence are expected to
induce a local magnetization $M$ perpendicular to the surface, which can readily be detected by the muon spin rotation ($\mu$SR) technique. That is, $M$ tilts the muon spin rotation axis from $B_{\text{par}}$ and hence causes the change in the profile of $\mu$SR spectrum. For example, if the induced $M$ is static, the asymmetry-oscillation amplitude $A_{\text{pp}}$ should decrease as $A_{\text{pp}} \propto \sin \beta$ with increasing $M$, when the incident muon spin is set parallel or antiparallel with its translational momentum, where $\beta$ is the angle between the total field $B$ and muon translational momentum as shown in Fig. 1. If $M$ possesses a dynamically fluctuating component, then the motional-narrowed muon spin depolarization rate is expected to be dependent on the incident muon spin direction.[4,5]

The effect of $B_{\text{par}}$ is not self-evident, because it tends to align electron spins along its direction. So, the magnitude of $B_{\text{par}}$ should be adjusted to be small and just enough to break the time reversal symmetry. Its criterion is discussed later.

The experimental study on the spin state in the topological insulators has its difficulty in that the spin current of spin-locked electrons cannot be controlled by a charge current because of their extremely short spin relaxation time, which is bound by momentum relaxation. The challenge of investing the spin current has so far been made by utilizing rather special techniques such as the spin-resolved ARPES or magnetic-tip-employed STM.[6-9] The present $\mu$SR-based method has some merits compared with other probes: it does not require the extraordinary cleanness of surfaces, which was a must for ARPES. The second merit is that it is free from the need to suppress the bulk conductivity, and does not require an extra doping for a fine tuning of the chemical potential.

Before describing experimental procedures, it must be referred here that the electron wave function dealt with many theoretical arguments reported so far has been a composite of real up spins and real down spins.[1,2] Therefore, the spin-texture proposed by those theories may not correspond to a real spin. This means that the spin polarization of spin-locked electrons in the topological insulators must carefully be investigated experimentally.

The present study bears its importance since the spin-locking governs the anomalous

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**Figure 1:** Schematic diagram for an expected asymmetry oscillation amplitude $A_{\text{pp}}$ in the presence of $B_{\text{par}}$ and induced magnetization $M$, when the implanted muon spin $\vec{S}_{\mu}$ is polarized antiparallel with the incident beam (left) or perpendicular (right). $\beta$ is the angle between the incident beam and the muon rotation axis ($\vec{B}$).

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**Figure 2:** A typical LE-$\mu$SR spectrum at 5 K and under $B_{\text{par}} = 100$ Oe applied parallel with the sample surface and perpendicular to the muon beam with $E_{\text{in}} = 1$ keV. The curve is the exponentially decaying sinusoidal function fitted in the region $t > 1\mu s$. The inset shows the raw output of counter at the left and right side detectors. The curves show exponentially decaying sinusoidal function fitted in the region $t > 1\mu s$. 

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suppression of back scattering of the surface conduction electrons, and hence the robustness of metallicity against randomness. Therefore the study of spin-locking will give us a deep insight for understanding the ground state of two dimensional electron systems, which have long been a key issue in the condensed matter physics.[10] In this article, we show our recent and preliminary results of the low energy (LE) μSR investigation on the spin state within the surface conducting layer of the tetradymite compound Bi$_{1.5}$Sb$_{0.5}$TeSe$_2$.

2 Experimental

The target sample Bi$_{1.5}$Sb$_{0.5}$TeSe$_2$ was a 60 nm-thick film, evaporated on mica plates [11,12] with the c-axis perpendicular to the plates. The μSR measurements were performed at the Paul Scherrer Institute utilizing the Low-Energy Muon Facility (LEM). Four plates with an entire size of 400mm$^2$ were glued with Ag-paste on the Ni-plated sample holder, which was set perpendicular to the muon beam. In order to make sure the electrical contact between the sample and base plate, a few drops of Ag-paste was dribbled at a corner of each plate.

Considering the result of Monte-Carlo calculations on muon stopping profiles for Bi$_2$Te$_3$, performed in-advance, the implanted muon energy $E_{in}$ was chosen to be 1 keV so that 46 % of muons stop within the conducting surface layer of 20 nm. For reference, measurements with $E_{in} = 3$ keV, for which 11 % muons stop within the surface layer, while others sense bulk part, were also done.

For the choice of magnitude in $B_{par}$, we simply adopted the criterion that the time-reversal symmetry of entire surface electron systems is broken when more than a flux quantum penetrates a coherent wave packet formed by electrons. This estimates $B_{par}$ to be 50 Oe if the inelastic scattering length $\xi$ reaches 1 μm at low temperatures.[13] In the present measurements, we chose the two values $B_{par} = 30$ and 100 Oe, which are slightly below and above the criterion.

The sample was cooled down slowly in order to avoid cracks in the surface, that is, in about 8 hours from the room temperature to 5 K, where all the data were taken. μSR spectra were measured with several directions of incident muon spins within a horizontal plane, that is, from +90° (directed parallel with the

![Figure 3: Energy ($E_{in}$) and muon spin direction dependence of oscillating amplitude in the μSR spectra. The abscissa shows the spin direction of implanted muon spin; the zero indicates the angle where the muon spin is parallel with the sample plate.](image)

![Figure 4: The fast component of muon spin depolarization curves, which are defined as $A_{fast}(t) = A(t) - (A_{pp}/2) \cos(\omega t + \phi) e^{-\Delta t}$. The details of parameters are described in text.](image)
beam) to $-90^\circ$ (antiparallel with the beam), controlled by the spin-rotator.[14] The time evolution of muon spin depolarization was measured as the L-R asymmetry $A(t)$, which is defined as the relative difference in counts between the left counters and the right one. The typical statistics of each measurement was $5\times10^6$ events in the entire experiment.

3 Results and Discussion

In Fig. 2, we show typical depolarization curves taken at 5 K for $E_{\text{in}} = 1$ keV. The overall time-evolution of asymmetry $A(t)$ at $t > 0.4$ μs was well understood in terms of a simple oscillation with exponential decay, that is, $(A_{\text{pp}}/2)\cos(\omega t + \phi) e^{-\lambda t}$, where $A_{\text{pp}}$, $\omega$, $\phi$ and $\lambda$ are the fitting parameters. The amplitude of oscillation $A_{\text{pp}}$ is plotted against the incident muon spin direction in Fig. 3, where one notes a slight but finite change in $A_{\text{pp}}$ with the incident muon spin direction. The difference between the data of surface ($E_{\text{in}} = 1$ keV) and the bulk (3 keV) at some angles such as at $-90^\circ$ exceeds the range of error bars. This indicates that our trial was successful in that muon spectra do probe, if partly, the surface contribution.

However, the dependence on the incident muon spin direction differs from that expected: a peak appears at the angle of $-45$ deg. The asymmetric profile against the muon spin angle cannot be explained. These results indicate that the method does not detect any static and uniform magnetization within the sample surface in the expected way. The other parameters, the decaying rate $\lambda \approx 0.14(1)$ μs$^{-1}$ and the rotation frequency $\omega$ stayed constant within error bars, independent of the incident muon spin direction.

Next, we look into the short time window of $t < 0.4$ μs shown in Fig. 2. One notes that there is an anomalously fast decaying component, which remarkably deviates from the fitting function. This fast component is observed in both the L and R detectors as seen in the inset. Its decaying rate is much smaller than the reported artifact depolarization caused by muons that miss the sample and hit Ni-plated base-plate[15,16], where the muons spins lose their polarization abruptly within 25 ns. We extract the fast component $A_{\text{fast}}(t)$ from the raw asymmetry $A(t)$ by subtracting the function $(A_{\text{pp}}/2)\cos(\omega t + \phi) e^{-\lambda t}$ shown above, and plot the residual curves in Fig. 4. They showed, if roughly speaking, the exponential-type decay with the rate of 10-20 μs$^{-1}$. The appearance of this fast decay in the short time window does not crucially depend on the detail of subtracting fitting function. However, for the determination of functional form of the fast decay, including rate, further measurements with higher statistics are required. We here focus attention on its initial asymmetry $A_{\text{fast}}(0)$, which is dependent both on the incident muon spin direction and also on $E_{\text{in}}$. We subtract the bulk-dominant data $A_{\text{fast}}(0)_{3\text{keV}}$ from the surface-dominant one $A_{\text{fast}}(0)_{1\text{keV}}$ and plot the difference in Fig. 5. Both the data under $B_{\text{par}} = 30$ and 100 Oe were positive for any muon spin direction, not crucially dependent on $B_{\text{par}}$, and took maximum at around zero, where the incident muon spin is directed parallel with the sample surface. Its positive sign suggests that the fast depolarization originates within the surface. However, at this stage, we cannot determine the origin of its significant dependence on the incident muon spin direction.
We refer why such a fast depolarization appears in the target compound consisting of all non-magnetic ions, which are not expected to bear a large spin fluctuation. Therefore, the observed fast decay is considered to be caused by a large hyperfine coupling, which enhances the small electron spin fluctuation to produce a large hyperfine field around the injected muon spins. This can be possible if one considers the Fermi-contact term in the conductive surface of the topological insulators.

Finally, we admit that these preliminary data may include more or less the effect of apparatus origin, for example, the effect of Ni-plated base plate. In order to conclude the validity of the method and hence the nature of the observed fast depolarization component, that is, whether or not it is related to the spin texture of topological insulators, further reference experiments for different $B_{par}$ and for a base-plate made of different material are necessary, and are now in progress.

Summary

The new method to study the surface spin texture of topological insulators utilizing LE-μSR has been proposed and applied to the on the quaternary tetradymite compound Bi$_{1.5}$Sb$_{0.5}$TeSe$_2$. The spin state in the surface layer of 10 nm thick was investigated by 1 keV muon beam at low temperature 5 K and under the parallel field of $B_{par} = 30$ or 100 Oe. The anomalously-fast muon spin depolarization, dependent on the initial muon spin direction, was observed in a very short time window $t < 0.4 \mu$s. In order to determine its origin, further reference measurements are necessary.

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