Measurement of μ^+ Relaxation Rates in Al and Mg Alloys for the Precise μ^+ Transverse Polarization Experiment TREK at J-PARC

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Abstract

The J-PARC TREK experiment will search for violation of time reversal invariance (T) in the $K^+ \rightarrow \pi^0\mu^+\nu$ decay. The transverse muon polarization (P_T) in stopped kaon decay will be measured with high precision (10^{-4}). An active polarimeter will be employed to stop muons and to detect decay positron asymmetry at the same time. The selection of the stopper material is an important issue. In a longitudinal and transverse field μSR experiment at TRIUMF, the muon spin relaxation rates have been measured for alloys of Al and Mg to find the best candidate stopper material. Almost all the alloys tested showed no significant relaxation.

Key words: T violation, kaon decay, muon transverse polarization, active muon polarimeter, Al and Mg alloys

1. TREK experiment

The violation of time reversal invariance (T) is an important issue in particle physics and many high precision searches for T-violation have been performed. We have planned an upgrade of our previous KEK experiment to measure the transverse muon polarization (P_T) in the $K^+ \rightarrow \pi^0\mu^+\nu(K_{\mu3})$ decays using a positive kaon beam in the Hadron Experimental Facility at J-PARC. P_T, with its T-odd character and with the negligibly small spurious effects involved, is a very clear signal of T violation. Due to the CPT theorem T-violation is equivalent to CP-violation. Therefore, such measurements also provide new information about the sources of CP-violation. Since the contribution of the Standard Model to P_T is very small ($< 10^{-7}$) and the spurious effects from final state interactions are also very small ($< 10^{-5}$), an experimental observation of P_T in the region of $10^{-3} \sim 10^{-5}$ indicates the existence of CP-violation sources other than that contained in the Standard Model. Namely, this would lead to a discovery of new physics. Such new sources of CP-violation are regarded to be necessary to explain the baryon asymmetry in the universe. In fact, there are several non-standard theoretical models which allow a sizable P_T such as multi-Higgs doublet model and the R-parity violating supersymmetric model (SUSY) which should be explored also in the LHC era. The current most stringent limit on P_T comes from our previous KEK-PS E246 experiment with $P_T = -0.0017 \pm 0.0023(stat) \pm 0.0011$ [1]. The error was dominated by the statistical error. The J-PARC TREK experiment should improve the sensitivity by at least a factor of 20 and reach $\delta P_T \sim 10^{-4}$ [2] by using a K^+ beam with about 20 times higher intensity.

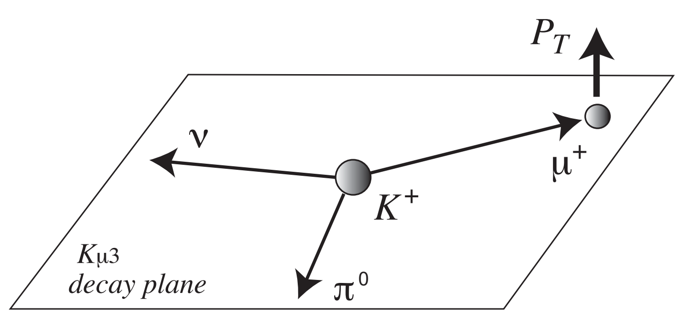

Fig. 1. Transverse muon polarization in the $K^+ \rightarrow \pi^0\mu^+\nu$ decays.

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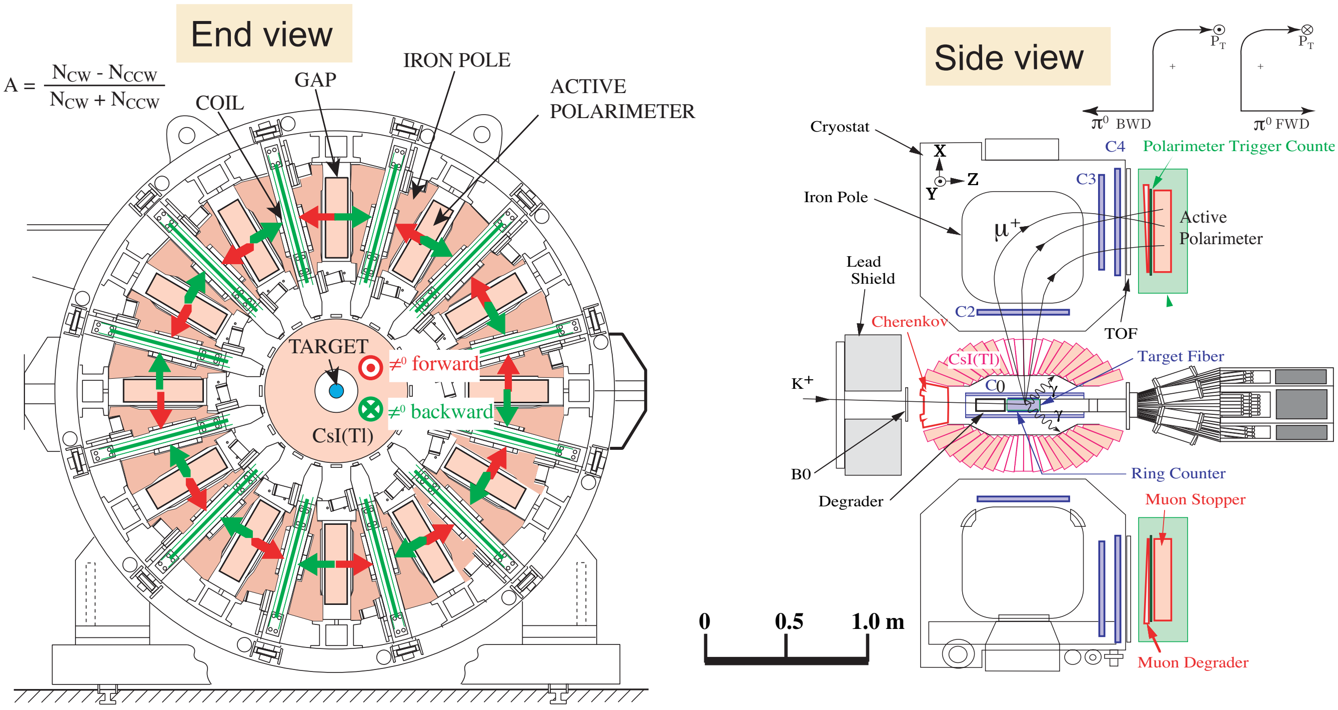

Fig. 2. TREK experimental setup with the Superconducting Toroidal Spectrometer.

2. Precise measurement of transverse muon polarization

In the $K_{\mu3}$ decay the predominant muon polarization component is the in-plane polarization and it has the value of unity. Therefore, the experiment has to detect a very small transverse component in the presence of a much larger (10^4) background. We will make a double ratio measurement as was also adopted in the E246 experiment by using the Toroidal Spectrometer setup and stopping the K^+ beam in the target. In the isotropic decay kinematics of K^+ at rest, one observes the regions in which P_T has opposite signs. We select the π^0 decay kinematic region in the forward direction (f) and backward direction (b) relative to the beam (or spectrometer) axis. Then, P_T in the muon polarimeter arranged in the 12 spectrometer gaps lies azimuthally (Fig.2). The T violating positron asymmetry A_T can be deduced as

$$A_T = \frac{A_f - A_b}{2} \tag{1}$$

with the e^+ emission clockwise and counter-clockwise asymmetries A_f and A_b defined as

$$A_{f(b)} = \frac{N^{cw}_{f(b)} - N^{ccw}_{f(b)}}{N^{cw}_{f(b)} + N^{ccw}_{f(b)}}. \tag{2}$$

In the subtraction (Eq.1) almost all the potential systematic errors can be eliminated. P_T can be deduced from A_T using the analyzer power coefficient α and the kinematical attenuation function $< \cos\theta_T >$ [1] to be

$$P_T = A_T/(\alpha < \cos\theta_T >). \tag{3}$$

The effect of the in-plane polarization is already absent in A_f and A_b, and its admixture to P_T due to decay phase space deformation, if any, can also be eliminated by taking a summation of A over the 12 gaps. An inherent source of systematic error, however, comes from the possible misalignment of the polarimeter relative to the active stopper as well as to the external field. In the TREK experiment an innovative method to correct for the possible misalignment using the $K_{\mu3}$ data will be employed in order to suppress the associated systematic error down to less than 10^{-4}. Thus, the detection of P_T with a sensitivity of 10^{-4} is feasible thanks to the expected statistical accuracy of 10^{-4} at J-PARC.

3. Active muon polarimeter

The muon polarimeter is the most essential component of the TREK detector. We have designed a so-called active polarimeter, in which the muon stopper and the decay positron tracker are combined. This scheme is quite different from the usual μSR setup with a separated muon stopping target and positron counter system. Our previous E246 experiment employed such a separate so-called passive polarimeter system. However, in our TREK polarimeter the muons will be stopped in an array of stopper plates and the gaps will serve as a drift chamber to detect the decay positrons and also the incident μ^+ (Fig.3). The current design has a gap of 8 mm and a plate thickness of 2.5 mm which should provide a muon stopping efficiency of nearly 90%. The advantage of this scheme is three-fold. First, we can perform a nearly background-free measurement, since we will identify each muon stopping point (decay vertex) and the decay positron track. Hence when we plot the e^+ time spectrum, the constant background should be essentially zero. Secondly, the detection efficiency of the e^+ is 100% because of the total solid angle coverage, which is also quite different from a normal μSR measurement. Thirdly, we will determine the e^+ emission angle from the tracking and we will measure the e^+ energy from the number of stopper plates which have been penetrated. This will increase the polarization analyzing power drastically, compared with our E246 detector. For a high-precision muon polarimeter the stopper material should be structurally strong and it should also produce a very small muon spin depolarization after stopping so as not to influence the subsequent P_T measurement.

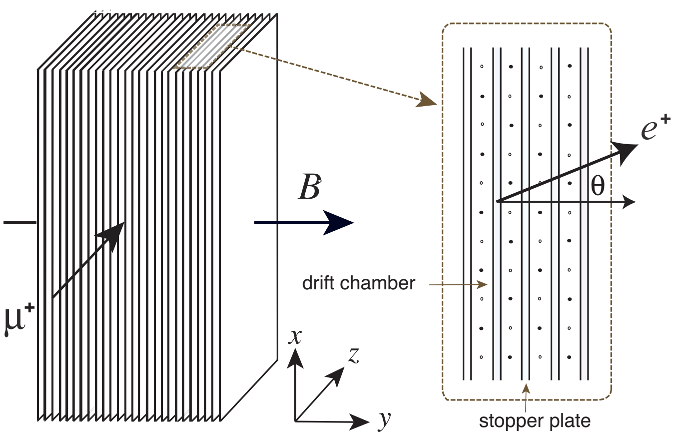

Fig. 3. Schematic view of the active muon polarimeter for one sector. Muons are stopped in the stopper plates. The field strength of B is 0.03 T.

4. Muon spin relaxation in alloys of light elements

It is very important that the stopper material has no significant muon spin depolarization including solid-state spin relaxation in matter, in order not only to achieve the highest sensitivity but also to avoid the possible material lot dependence among the 12 polarimeters. Another requirement is that the stopper should be a light element to minimize the e^+ multiple scattering. Pure Al is known to be one of the best materials satisfying these conditions [4]. The stopper plates, however, have to serve as the structural element of the drift chamber as well as the ground electrode. Considering all these requirements, we have focused on Al and Mg and their alloys while excluding possibly better materials, such as Be or Li for practical reasons. There have been a few studies of muon relaxation rates in alloys of Al and Mg [5] but no data was found for the commercially available industrial materials or their alloys. In order to have a number of possible candidate materials when designing the drift chamber we decided to perform μSR measurements on several Al and Mg alloys.

5. TRIUMF S1120 experiment

The measurements were performed on the TRIUMF M20 beamline with a 100% polarized surface muon beam using the standard OMNI LAMPF setup [3]. Longitudinal field (LF) as well as transverse field (TF) μSR measurements were conducted under the same conditions expected at the TREK experiment, namely room temperature ($\sim 20°$) and a 30 mT external magnetic field. (The LF measurements are more relevant to the TREK asymmetry measurement.) This field strength is regarded to be the minimum value necessary to decouple the possible earth and stray fields in the J-PARC experimental area and also to decouple the possible nuclear dipolar fields acting on the muons when they are stopped at the trapping site *etc.* Samples with a size of 25 mm $\times$ 25 mm with a typical thickness of 1 mm were prepared from commercially obtained test materials. The beam intensity was 4×10^4/s with a stopping fraction of 60% in the sample. The total positron event rate in L/R+U/D (in TF) or F/B (in LF) counters was 1.2×10^3/s. Here, L, R, U, D, F, and B mean "Left", "Right", "Up", "Down", "Forward" and "Backward", respectively. The positron time spectrum was measured up to 10μs. We accumulated $\sim 4 \times 10^6$ events in each run. Since we were interested in a very small relaxation rate, special care was taken about the field uniformity on the sample and the current stability of the magnet power supply. It was confirmed that both effects were insignificant. The positron asymmetry (raw counter asymmetry) was typically 0.27 indicating a good experimental condition for the relaxation rate measurement.

6. Result and conclusion

The positron time spectra were fitted to the standard analysis functions at TRIUMF and the relaxation rates were deduced. In almost all samples tested a small relaxation rate was observed. Because of the small damping rate the fit was sensitive to the initial asymmetry (or instrumental counter asymmetry), and it was sometimes necessary to fix this quantity when fitting the relaxation rate λ. Therefore, there might have been a small ambiguity in the fitting, but the final result was not much affected. Table 1 gives the results from the typical fitting. The small relaxation rate also made it difficult to determine the relaxation func-

Table 1
Muon spin relaxation rates in Al and Mg alloys in transverse field (λ^{TF}) and longitudinal field (λ^{LF}) measurements.

	Sample	Main impurities (%)	$\lambda^{TF}[\mu s^{-1}]^{1)}$	$\lambda^{LF}[\mu s^{-1}]^{2)}$
Al	pure Al (annealed)		0.00397±0.00090	0.01341±0.00040
	pure Al (99.95%)	Fe:0.29	0.00760±0.00091	0.00074±0.00115
	pure Al (> 99.99%)		0.00338±0.00087	0.01491±0.00359
	A5052	Mg:2.5, Fe:0.27, Cr:0.21	0.01074±0.00076	0.01129±0.00127
	A6063	Mg:0.51, Si:0.44, Fe:0.18	0.01564±0.00090	0.01767±0.00311
	A2017	Fe:3.8, Si:0.66, Mg:0.5, Cu:0.49, Mn:0.47	0.04840±0.00100	0.01014±0.00488
Mg	pure Mg (99.95%)	Mn:0.01, Al:0.06, Fe:0.05	0.00327±0.00086	0.01503±0.00262
	AZ31	Al:2.91, Zn:0.85, Mn:0.4, Si:0.2	0.00115±0.00091	0.00081±0.00244
	AZ31-PE	Al:2.80, Zn:0.93	0.00041±0.00092	0.01372±0.01081
	ZK60	Zn:5.60, Zr:0.52	0.00030±0.00111	0.00741±0.00299
	Z6	Zn:6.2	0.00000±0.00087	0.01799±0.00159
	AM60	Al:5.88, Mn:0.32	0.00000±0.00043	0.01052±0.00340
	AZ91	Al:9.22, Zn:0.69, Si:0.31	0.00270±0.00093	0.01912±0.00277

1) fit with an exponential relaxation function $e^{-\lambda t}$, 2) fit with a Gaussian relaxation function $e^{-\lambda^2 t^2}$.

tion uniquely. For TF reasonably good fits were obtained with an exponential type ($e^{-\lambda t}$) relaxation, while for LF a Gaussian type relaxation ($e^{-\lambda^2 t^2}$) provided rather stable fit results.

We found that all the sample tested showed very small relaxation rates and they could all be used as the muon stopper material, except for the Al alloy A2017, which has relatively large concentration of magnetic impurity elements such as 3.8% Fe, and showed a rather large λ^{TF} relaxation rate. Hence the selection of the stopper material from the tested samples can now be based on more practical conditions, such as its suitability as the chamber electrode and structural component of the polarimeter. Now the selection is being made.

The small relaxation rates observed in the candidate stopper materials ensure the highest sensitivity of the TREK experiment. And we do not have to worry about any effects related muon spin depolarization. The size of the relaxation rates is regarded to be sufficiently small enough to suppress the systematic error to less than 10^{-4}, although there is no direct relation between the relaxation rate and the systematic error in the current TREK experimental scheme.

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