Cosmic-ray muon spin rotation in Fe and industrial application

2014 J. Phys.: Conf. Ser. 551 012064

(http://iopscience.iop.org/1742-6596/551/1/012064)

Cosmic-ray muon spin rotation in Fe and industrial application

K Nagamine[1,2,3*], T Fujimaki[4], T Hashimoto[4,5], M Tsukamoto[4], S Kubota[4], T Hirai[4,6], A Manabe[4], Y Tomisawa[4,7], A D Pant[4] and E Torikai[4]

[1] Atomic Physics Laboratory, RIKEN, 2-1 Hirosawa, Wako, Saitama 351-0198, Japan
[2] Department of Physics and Astronomy, University of California, Riverside, USA
[3] Muon Science Laboratory, IMSS. KEK, Oho, Tsukuba, Ibaraki, Japan
[4] Interdisciplinary Graduate School of Medicine and Engineering, University of Yamanashi, 4-3-11 Takeda, Kofu, 400-8511, Japan

E-mail: k.nagamine@riken.jp

Abstract. Spin polarized positive muons contained in the cosmic-rays were stopped in the Fe plates providing a characteristic spin rotation signal of decay positrons. This signal along with the decay lifetime of the negative muons can be used as a non-invasive radiographic measurement method for a characterization of the inner structure of the aged architectures. Principle, results of test experiments and future prospects are described.

1. Introduction

After a history of more than 500 years of the modern life, most of the large-scale architectures such as buildings, bridges, highway roads, dams, etc. are coming to the end of their lives. There, usual happenings inside these architectures are corrosions of the iron rods in the reinforced concretes. However, it is not easy to examine the status of these iron rods non-invasively, namely, without breaking the architectures.

In order to inspect the inner structure of the large scale architectures, a use of cosmic-ray muon is quite effective. In fact, by measuring the positional distribution of the intensity attenuation of the penetrating cosmic-rays, the inner-structure of blast furnaces have been studied [1], based upon the experiences of radiography of the volcanic mountains [2, 3]. Recently, in order to explore the inner status of the damaged Fukushima nuclear reactors, use of this cosmic-ray muon transmission radiography was proposed [4, 5] along with the multiple scattering method [6].

Here, we propose a different and new use of the cosmic-ray muons to explore near-surface (20 cm thick from the surface) structure of the architecture by detecting the μSR signal of decay positrons and the lifetime of decay electrons from the cosmic-ray muons stopped inside the objectives.

[5] Present address: Yazaki Cooperation
[6] Present address: Yamato Scientific Co., Ltd.
[7] Present address: Kowa Pharmaceutical Co., Ltd.

2. Principle

2.1. Nature of cosmic-ray muons

Cosmic-ray muons at the sea level of the earth are known to have the following properties; a characteristic Zenith-angle dependent energy spectrum with common natures of high energy (GeV to TeV) and low intensity ($1/(cm)^2/min$ in vertical direction) [7], a mixed charge state (μ^+ (0.6) and μ^- (0.4)) and a partial spin polarization (-0.33 for μ^+ [8]). Because of the high energy nature, a stopping distribution of the cosmic-ray muon in concrete extends from cm to more than 100 m in depth.

2.2. The present method: reflection radiography of stopping cosmic-ray muons

Thus, by detecting a signal of the decay positrons and decay electrons whose energies are up to 50 MeV from various selected position of the stopping muons inside the objective, one can obtain a radiographic imaging information such as a spatial distribution of microscopic magnetism from the μ^+SR signal and an element distribution from the amplitude distributions of components with different μ^- free-decay lifetime [9]. As for a classification of the radiography method, we can consider this signal as a reflection signal which is a signal from the objective in the direction opposite to the direction of the injected probing radiation.

The signal N(t) of time dependent intensity change of decay positrons and decay electrons with reference to the time of stopping of the incoming cosmic-ray muons detected for an area of each stopping position of the cosmic-ray muons can be written as follows. Here, the stopping position can be obtained by the direction of the incoming cosmic-ray muons determined by a telescope of more than two arrays of the segmented counters [3].

$$N(t) = N_0 \left[\alpha \; \mathrm{e}^{-t/\tau(0)} \{ 1 + \sum_i (A_i \mathrm{e}^{-\lambda(i)t} \cos(\omega_i t + \phi_i)\} + (1-\alpha) \sum_j P_j \; \mathrm{e}^{-t/\tau(j)} + C \right] \; , \qquad (1)$$

where α: a fraction of positive muon in the cosmic-ray, $\tau(0)$: μ^+ lifetime, A_i: decay positron asymmetry parameter in the ith material including μ^+ polarization, ω_i: μ^+ spin precession due to internal field of the ith material, $\lambda(i)$: relaxation rate of the μ^+ spin precession due to the ith internal field, P_j: fraction of the μ^- stopping in the jth material and $\tau(j)$: μ^- lifetime in the jth material, respectively.

3. Test experiments

As the first step, time-spectrum of the decay positrons and electrons from the cosmic-ray muons stopping in Fe plate of regular 99% purity Fe plate (2 cm thick) and in concrete plate of commercial use (6 cm thick) were measured separately as shown in Fig. 1, where each counter is a plastic scintillator with a size of 10 cm width 100 cm long and 3 cm thick. The results are presented in Fig. 2 and 3. There, the data for the FWD (BWD) direction where decay electrons/positrons were detected along (opposite to) the direction of incoming vertical cosmic-ray muons were presented.

In the present set-up, the following weak points existed. Because of a relatively slow fall off time of the output signals of the plastic scintillator, the BWD event which needs anti-coincidence of the incoming muon, effective dead-time existed up to 150 ns after muon stop. Because of this weak point, the μ^+SR data was taken only by the FWD data. Also, stopping events in D1$\sim$D6 counters are included in the stopped muon events in the data for either Fe or concrete.

In Fe, μ^- takes strong nuclear capture resulting free-decay lifetime of 200 ns [9], while polarized μ^+ is expected to feel the internal field of ferromagnetic metal causing spin precession of 50 MHz [10]. On the other hand, in concrete whose major elements are Si ($\sim$30%) and O ($\sim$50%), μ^- takes weak nuclear capture resulting free-decay lifetime of 760 ns for Si and 1830 ns for O [9], while polarized μ^+ is expected to feel no internal field causing no spin precession.

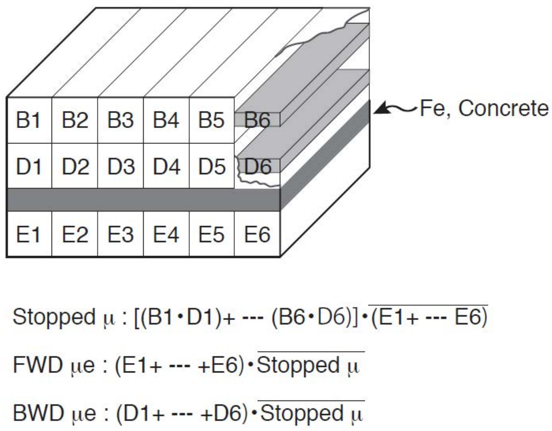

Figure 1. Counter geometry and logics of decay electron/positron detection from stopped muons in the test experiment. Inside each counter box, a plastic scintillator with the size of 3 cm thick, 10 cm wide and 100 cm long is located.

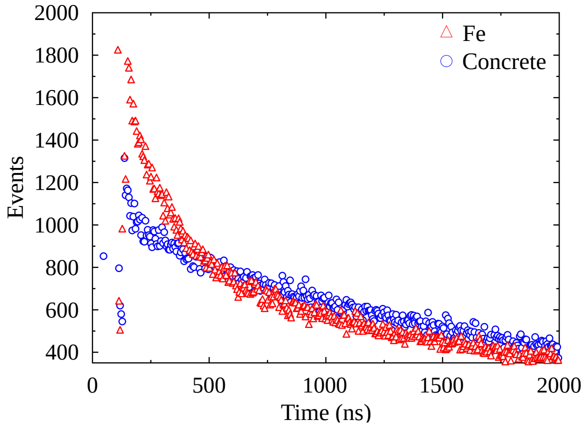

Figure 2. The time spectrum in BWD geometry from stopped cosmic-ray muons in concrete and Fe observed in the test experiment. The 200 ns lifetime component from negative muons stopped in Fe is clearly seen.

Fitting analysis for Eq. (1) were made by assuming $\tau(0)$=2.2 μs and $\tau(Fe)$ =0.2 μs [9], yielding the values listed in Table 1. Thus, μSR in Fe with a precession frequency of around 50 MHz [10] was obtained as expected. The obtained values of A_{Fe} and B_{Fe} (μ^+ internal magnetic field in Fe converted from ω_{Fe}) obtained from ω_{Fe} are also consistent as expected; 1/3 (reduction by asymmetry average) $\times$ 0.6 (charge fraction)$\times$ 0.33 (μ^+ polarization) = 0.066 and 3595 Oe obtained in the accelerator muon experiment [10], respectively. On the other hand, the measured relaxation rate of the μ^+ in usual iron plates looks faster than that of the μ^+ in pure Fe at room temperature observed in accelerator muon experiment (0.80 μs^{-1}) [10], suggesting the effect of corrosion in usual iron plates.

At the same time, as seen in Fig. 2, earlier part of the time spectrum corresponding to the μ^- free-decay from Fe with the lifetime of 200 ns was correctly detected. The consistent data was also obtained for concrete.

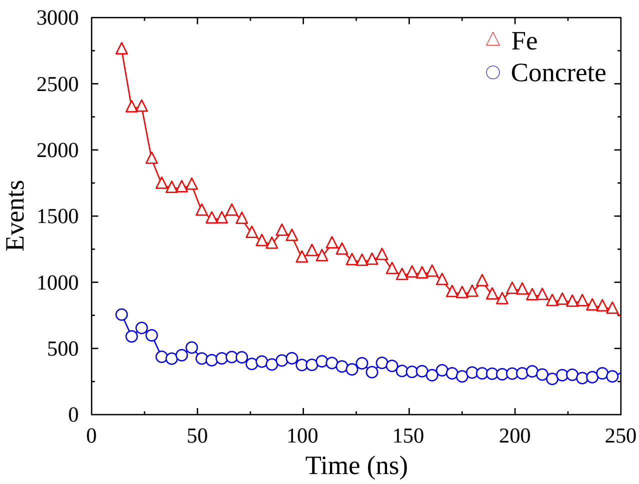

Figure 3. Observed ZF spin rotation time spectrum from cosmic-ray muons stopped in Fe (46 days of measurement time) and concrete (20 days). Data in the FWD geometry are shown. Existence of 50 MHz positive muon spin rotation signal in Fe is obvious.

Table 1. Summary of the cosmic-ray μ^+ spin rotation in Fe.

A_{Fe}(%)	B_{Fe}(Oe)	$\lambda(i)(\mu s^{-1})$
5.7(2.2)	3390(130)	25(13)

4. Some considerations

4.1. Next steps toward the goal of the present method

The goal of the present new reflection radiography method by detection of the decay e^+/e^- from stopped cosmic-ray muons can be summarized as follows,

1. Element analysis by the μ^- lifetime method; mapping of the profile of the Fe rods without any destruction.
2. Material analysis by μ^+SR method; by measuring spin relaxation rate of the μ^+, one can learn the corrosion status in comparison with the systematic reference data to be taken at the accelerator facilities.
3. Monitoring 20 cm depth in concrete with a spatial resolution of close to $(1\,\mathrm{cm})^2$

Following success of the present test experiment, we are considering to take the following next steps. (1) Imaging of the reinforced concrete to detect the Fe rod status; by placing two telescope counters for muon tracking in front of the decay e^+ and e^- detector (see Fig. 4), where all the signals of the decay e^+/e^- will be obtained with reference to each muon stopping position; (2) systematic detection of corrosion status of the Fe rod through a change of the μ^+SR data, combined with the planned studies at the accelerator facilities of the continuous muons as described later. (3) design optimization of the imaging device for the re-enforced architectures will be conducted. Then direct monitoring experiment of the Fe rods status will be started for the big architectures like buildings, highways, dams, etc.

4.2. Ambiguities in stopping position determination

In the present method, stopping position of the cosmic-ray muons is considered to be determined by the trajectory determination just in front of the objective. A lateral and longitudinal spread ($D_\perp$, $D_\parallel$) of the parallel pencil beam after the range R_0 of stopping can be estimated following the phenomenological formula [11]; $D_\perp = 7\times10^{-2}\times R_0^{0.92}$, $D_\parallel = 2.6\times10^{-2}\times R_0^{0.94}$. Thus, ambiguity in determining the stopping position at 20 cm depth corresponds to the range in concrete of 50 MeV decay e^+/e^- is around 1 cm.

4.3. Expected role of the μ^+SR data of the imbedded Fe

The most important feature of the μ^+SR in Fe is the fact that one can probe a microscopic molecular level characteristic from outside. By stopping cosmic-ray muons in reinforced concrete, this probing can be done up to the depth of 20 cm from where the decay e^+/e^- can be coming out to the E-counter placed as shown in Fig. 4.

On the other hand, corrosion of the steel in reinforced concrete (RC) is the central problem causing a serious damage in big architectures. The alkalinity of the concrete usually protects the imbedded Fe from corrosion. However, during a long time use in 100 years or longer, various electrochemical reactions proceed between iron and dissolved ions in the vicinity of the iron to create corrosion [12]. This corrosion causes a damage of the reinforced concrete in the form of expansion, cracking and destruction of the covered concrete. It is expected that magnitude/dynamics of the microscopic internal magnetic fields at the interstitial sites of Fe under corrosion is significantly different from those of pure iron crystal.

In order to establish the reference data, the μ^+SR experiment will be conducted at accelerator facility of the continuous muon beam for the following Fe materials; Fe rod extracted from fresh RC, that from expanded RC and that from destroyed RC. Although the relevant experimental data do not exist at all, considering from theoretical understanding of the μ^+ hyperfine fields in Fe [13], a significant difference might be expected for these different stages of RC.

4.4. Feasibility considerations

In order to confirm the feasibility, let us consider the necessary measurement time length (years) for the present method to monitor the inside of the actual building with reference to the test experiment mentioned above.

First, the number of the μ^+SR events and the decay μ^- to e^- events from the cosmic-ray muons stopped in the sample can be written as follows,

$$N_{\mu e,\mu SR} = N_{stopped\,\mu} \times \Delta\Omega_{\mu e,\mu SR} \times \delta t = [I_{stopped\,CR\mu}(\theta_z, \Delta\Omega, \Delta R) \times \delta A] \times \Delta\Omega_{\mu e,\mu SR} \times \delta t \quad (2)$$

where $\theta_z, \Delta\Omega$ and ΔR are cosmic-ray Zenith-angle, solid angle and stopping range, respectively.

In the test experiment, the parameters in Eq. (2) can be written as follows,

$[I_{stopped\,CR\mu}](0°, 5/6 \times 2\pi, 5\,\text{cm} \quad \text{Fe})$, $\delta A = 60$ cm $\times$ 100 cm, $\Delta\Omega_{\mu e,\mu SR} = (1/2)2\pi$, $\delta t = 9$ days

In the case of an inspection of the re-enforced concrete building by employing the detection system as seen in Fig. 4, it is intended to identify the stopping position of the cosmic-ray muons in the unit of 3 cm$\times$3 cm by employing tracking detector with the resolution accordingly. There, the parameters of Eq. (2) become as follows,

$I_{stopped\,CR\mu}(80°, 0.45\times 2\pi, 20\,cm\,ReEnf.Concrete) \cong 0.27\times I_{stopped\,CR\mu}(0°, 5/6\times 2\pi, 5\,cm\,Fe)$,

$\delta A = 3$ cm $\times$ 3 cm, $\Delta\Omega_{\mu e,\mu SR} = (1/2)2\pi$,

$\delta t = 9$ days $\times (1/0.27) \times (60 \times 100/(3 \times 3)) = 61$ years for the same $N_{\mu e,\mu SR}$ of obtained in the test experiment.

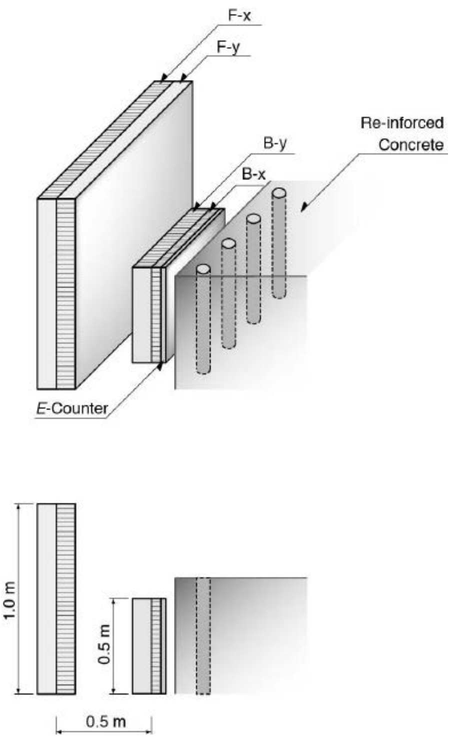

Figure 4. Proposed set-up for the reflection radiography using decay electron/positron from the stopped cosmic-ray muon. Muon beam tracking hodoscope is placed in front of decay e^+/e^- to determine muon stopping position.

There are several ideas to increase the event rates and decreasesubstantially the measurement time from 61 years. The followings are the present suggestions.

(1) Increase the sensitive area of the whole detection system by a factor of 4.

(2) Data rearrangement by summing up similar Fe region to inspect average chemical status of the Fe rods (×10).

Thus, required measurement time δt becomes 1.5 year. Obviously, once the application becomes to be proved as a feasible method, industrial application will be started, promoting a production of cheap and larger-scale detection systems. This development scenario should be started within a near-future.

5. Conclusion

As presented here, based upon the results of test experiments, feasibility considerations and combined use of well-established transmission radiography instrumentation, the cosmic-ray muons are ready to be used to explore inner structure of the reinforced concrete architectures. A large-scale industrial application will soon be opened.

References

[1] Nagamine K *et al.* 2005 *Proc. Jpn. Acad. Sci.* B **81** 257–260
[2] Nagamine K *et al.* 1995 *Nuclear Instruments and Methods* A **356** 585
[3] Nagamine K 2003 *Introductory Muon Science* (Cambridge: Cambridge University Press) pp 1–208
[4] Nagamine K 2011 *Urgent Proposal to KEK Director General*
[5] Fujii H *et al.* 2013 *Prog. Theor. Exp. Phys.* 073C01
[6] Morris C *et al.* 2012 *AIP Advances* **2** 042128
[7] Adair R K and Kasha H 1976 *Muon Physics* vol 1 ed V W Hughes and C S Wu (New York: Academic Press) p 323
[8] Turner R *et al.* 1971 *Phys. Rev.* D **4** 17
[9] Measday D F *et al.* 2001 *Phys. Reports* **354** 243
[10] Nishida N *et al.* 1977 *Solid State Comm.* **22** 235
[11] Fowler P H *et al.* 1961 *Nature* **189** 524
[12] Verbeck G J *et al.* 1975 *American Concrete Institute Special Publication* **49** 21
[13] Kanamori J *et al.* 1981 *Hyperfine Interactions* **8** 573