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Conventional to slow muon microscopy – a review

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ABSTRACT

Because of special characteristics (fully spin polarized and asymmetric decay to positron), muon acts as sensitive probe to study the local electronic and dynamics of materials. The muon of energy MeV or high, conventional muon, are used to study bulk properties of the materials. For the study of nanoscience, slow muon (20 eV - 30 keV) muon with low energy spread are essential that leads to development of slow muon microscopy. Introduction to muon microscopy, application of conventional muons and need of slow muon beam along with future prospects are briefly discussed.

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1. Introduction

Muon is an elementary particle of lepton family of 2nd generation of standard model of particles (Table 1). Its mass is about 207 times of electron mass and 1/9 times of proton mass as shown in Table 2. The gyromagnetic ratio of muon is around three times higher than that of proton which makes it more sensitive in materials. Muons are available from two ways - naturally, it is available in cosmic ray with 1 event per square cm per min with relatively higher energy (~GeV) [1], and another is from accelerators with high intensity (e.g., ~ 10^6 muons per sec in Japan Proton Accelerator Research Complex, J-PARC) and tunable energy. Muon born from decay of pion. In accelerators, high energy proton are bombarded to pion production target (usually graphite) and pions are produced ($p + p \rightarrow \pi^+ + p + n$). When the pion at rest decays (two body decay, Fig. 1) to muon and a neutrino ($\pi^+ \rightarrow \mu^+ + \nu_\mu$), due to conservation of momentum, muon and neutrino have equal and opposite momentum [2]. The pion is the zero spin particle and the spin of neutrino is antiparallel to momentum (negative helicity) which suggests that the spin of muon must be opposite to its momentum (Fig. 1). Thus muon has 100% spin polarization.

Muon decays to positron and two neutrinos ($\mu^+ \rightarrow e^+ + \nu_e + \overline{\nu_\mu}$) with life time 2.2 μs. Due to violation of parity in weak interaction, positrons are produced asymmetrically along the spin direction of muon at the time of decay. With these characteristics – fully spin polarized and asymmetric decay to positron, it works as sensitive magnetic (spin) probe to study the materials. Since it is sensitive even less than a Gauss magnetic field, it acts as sensitive probe to study the local electronic and spin states of materials through muon spin rotation and relaxation (μSR) method [1, 3].

Conserving the momentum, muon is 100% spin polarized. Here, p_i and S_i are used for momentum and spin of corresponding particles, respectively.

Table 1. Standard model of particles.

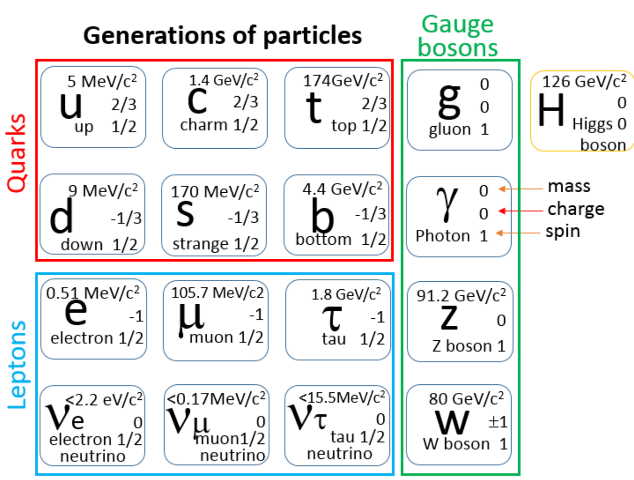

Table 2: Properties of electron, muon and proton.

Particle	Charge (e)	Spin	m/m_e	μ / μ_p	γ/2π (MHz/T)	τ (μ s)
e electron	±1	½	1	657	28025	∞
μ muon	±1	½	207	3.1833	135.5	2.1971
p proton	±1	½	1836	1	42.58	∞

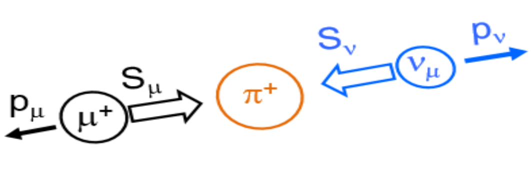

Fig. 1: Decay of pion ($\pi^+ \rightarrow \mu^+ + \nu_\mu$) at rest.

When the muons are produced from the pions at rest on the surface of pion production target (like graphite), such muons are called as surface muon. Energy of such surface muons is ~ 4.1 MeV (momentum ~ 29 MeV/c). And when the muons are produced from the pion in-flight and captured by strong magnets, then such muons are called as decay muons (momentum > 40 MeV/c). In this article conventional term is used for both surface and decays muons having energy of MeV order. On the other hand, slow muon are refereed as slowed-down surface muon to low energy (20 eV – 30 keV). Such slow muons can be stopped in the thin films of some nm depth from surface of sample however conventional muons needs thicker (~mm) samples to stop.

In addition to positive muons, negative muons are also being popular for study of elemental analysis [4]. When a negative muon incident in materials, it is attracted by atomic nuclei. Since its mass is much greater than that of an electron, it readily displaces an electron from an atom and rapidly drops down to the *1s* state. Consequently, emission of muonic X-ray can be observed [4, 5]. Analysis of such muonic X-ray provides the information about the elemental composition of materials as a non-destructive analysis method. In this review, we concentrate on only positive muon and its applications.

2. Advantages of muon microscopy

Muon acts as spin polarized probe so it behaves as a magnetic needle in materials. It can be applied at any temperature and without perturbation (without external field) of system. Its time window (10^{-11} – 10^{-5} s) is wider than other techniques (NMR, neutron and Mossbaur) [6] as shown in Fig. 2. Unlike electron and proton, when high energy muon incident into materials there are no braking radiation, pair production and nuclear reactions happened. It can approach to higher depth in the materials than other particles. It stops interstitial sites in near the high electron density. Its bound state with an electron known as muonium which is like a light isotope of hydrogen. It is an exotic atom made up of two lepton particles. It can predict/mimic the behavior of H in the materials. It also used to test the quantum electrodynamics (QED)

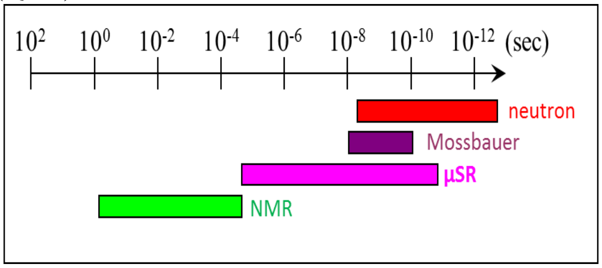

Fig. 2: Comparison of time window of different techniques. The μSR technique has wider time (~ 10^{-11} to 10^{-5} s) window than other methods.

3. μSR techniques

Initially in 1981, the term μSR was coined [8] as "μSR stands for Muon Spin Relaxation, Rotation, Resonance, Research, or what have you. The intention of the mnemonic acronym is to draw attention to the analogy with NMR and ESR, the range of whose applications is well known. Any study of the interactions of the muon spin by virtue of the asymmetric decay is considered μSR, but this definition is not intended to exclude any peripherally related phenomena, especially if relevant to the use of the muon's magnetic moment as a delicate probe of matter." In μSR technique, the spin polarization of muon is 100%. However in NMR and ESR, the polarization of the nuclear or electron spins is very far from 100%, so that a radio frequency or microwave photon is required to resonantly perturb the system and obtain a signal. When muons are incident on material, decayed positrons are collected by detectors around the sample (Fig. 3(a)). Time evolution of those positron provides the information about the material [3]. Suppose, F is positron events collected by forward counter and B is that by backward counter, then asymmetry = $(F - \alpha B) / (F + \alpha B) = A_0 G(t)$, where α is alpha factor that depends on efficiency of detectors and sample positions, A_0 is initial asymmetry, and G(t) is polarization function. The collections of some of G(t) are presented in musrfit program [9, 10].

In general, there are two geometrical set-ups for μSR measurements – transverse and longitudinal field μSR measurement (namely TF and LF measurement). When momentum of incident muon spin is parallel to external applied magnetic field it is known as longitudinal field measurement and when muon spin is perpendicular to applied field it is known as transverse field measurement (Fig. 3 (a,b,c)). Muon precesses around the field according to the Larmor precession.

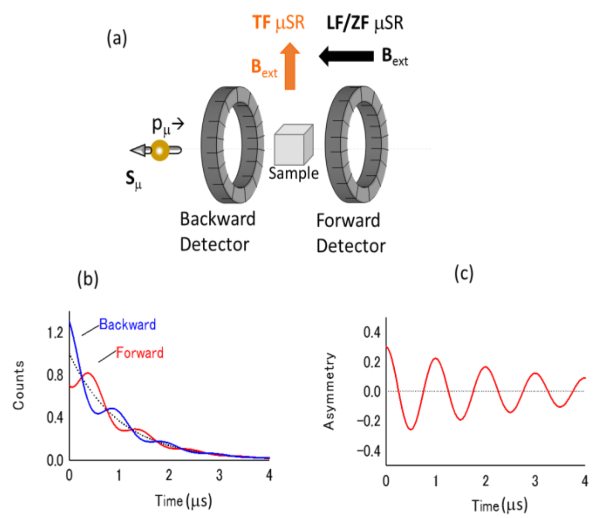

Fig. 3: Schematic diagram for μSR set-ups and spectrum. (a) Experimental set-up for transverse field (TF) and longitudinal field (LF) measurement, (note that the both measurements set up performed separately) (b) counts collected by forward and backward detectors at TF measurement, and (c) the muon time evolution spectra, asymmetry, at TF measurement.

4. Applications of conventional muons

When muon implanted into materials, it thermalizes very quickly (within ns) and its spin is not affected during thermalization. However the spin of muon is affected by the magnetic properties of environment of specimen. Depending on nature of materials and environment of stopping site of muon, it captures electron and form muonium or remained in same diamagnetic state. The polarization function, G(t), provides important information about the materials. Thus the muons are used to study the magnetism, superconductivity, molecular dynamics, particle physics, life science, new physics beyond standard model, etc. Researches in physics, chemistry and biology have been widened using conventional muons. For example, study of energy storage materials [11], semiconductor [12], semiconductor and insulators [13], life science [2, 14-17], polymer [18], particle physics [19, 20], and many more.

With the use of high intensity muons, there are some experiments like *g*-2/EDM, muon to electron conversion, etc. are being carrying out. The *g*-2 experiment is being carrying out by two independent groups - one in J-PARC [21] and another in Fermi National Lab [22] to achieve the higher precision on the value of anomalous magnetic moment of muon than the previous experiment in Brookhaven National laboratory group [19] and to discover the new physics beyond the Standard Model [19, 23].

Because of functional and dynamic complexity of biosamples, few literatures are available on use of muon for study of life phenomena. To the best knowledge of author, Nagamine et al [2] initiated the use of muon in biomaterials and explained the behavior based on muon labelled electron method [1]. Recently μSR method pointed out its application for cancer research [14] and diagnosis of disease [24]. Electron transfer in protein [17, 25] and photosynthesis processes have been studying intensively through experimentally and theoretically [26, 27].

Besides accelerator produced muon, cosmic muons are also useful for the study of non-destructive analysis of large scale architectures [28] and characterization of materials like study of trapped radioactive materials [29].

5. Need and development of slow muon beam

The conventional muon (~MeV energy or high) are stopped in a thick sample with broad stopping depth. With such high energy spread and incident energy, it can only be used to study the bulk properties of materials (schematic diagram presented in Fig. 4). For the study of thin film, layered material, surface/interface and nanoscience study, slow muon beam is required. K. Nagamine pointed out three methods for production of slow muons [30]. The generation of low energy muon through the cryogenic moderation method using Van der Waals solids such as solid Ar or N_2, which has been initiated at TRIUMF and is developed at PSI, Switzerland [31]. Second one is the laser resonant ionization of muonium produced from muonium generation materials [30]. This method was developed at KEK and then at RIKEN/RAL pulsed muon facilities [30] and now adopting in J-PARC, Japan [32-34]. Third one is the beam cooling method by using electromagnetic confinement as well as acceleration or deceleration after detecting the phase space of each injected conventional muon. At PSI, using continuous muon beam, the slow muon microscopy has been applied in different materials through user programs [35]. Using pulsed muon beam in J-PARC, the development of ultra slow muon beamline which is dedicated to slow muon microscopy is still in progress [33, 34]. The slow muons are successfully generated and transported to sample position [36]. Now we are struggling to enhance the intensity and optimize the beam parameters.

For the study of nanoscience and three dimensional visualization of materials, ultra slow muons are considered as promising tool. For this purpose, ultra slow muon microscope, an innovative instrumentation, is being developed in Japan Proton Accelerator Research Complex (J-PARC), Japan [37]. There are two beams – ultra slow muon beam (energy 20eV – 30keV, beam size < 10mm) for surface and interface study of materials with nm depth and muon microbeam (energy 200 keV – 1 MeV, beam size tens of micrometer). After re-acceleration of slow muon (to prepare coherent beam), another instrumentation - transmission muon microscope is also under development in J-PARC [38]. Main goal of this instrument is to prove the dual nature of muon (wave and particle) and to provide three dimensional imaging of small alive samples. It will fulfil the gap between optical microscope and transmission electron microscope.

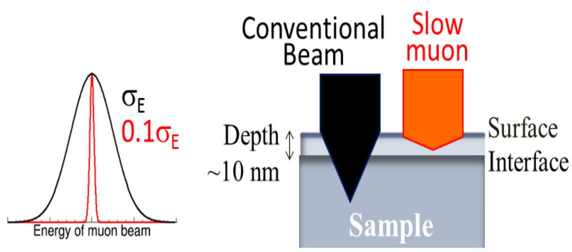

Fig. 4: Schematic diagram for effect of energy spread of muon beams (left figure) – need of slow muon for nanoscience. Slow muon can be controlled within nm depth however wide spread stopping depth for conventional muons (right figure).

6. Future perspectives

Ultra slow muon is promising tool to study the nanoscience. It can be used for both materials and life study. The use of slow muon to study the surface, interface and grain boundary of materials will help to advance the development of functional materials for devices and understanding the basic and advanced sciences. There are still some challenges regarding to development of high intensity and low tunable energy slow muon beam. Furthermore the application of slow muon to solution form or real biosample is another challenge because of need of high vacuum environment. Without using the sample cell (window), we can use slow muon on single crystal samples but it is still difficult to apply them to understand the role of hydration in real biosystems. The under developing micro muon beam (after acceleration) will be quite helpful to study the even intact biological cells [38]. Furthermore, the formation of μ+μ- atom and testing of various fundamental laws of physics will also be possible with the application of slow muon beam at J-PARC [39].

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