Muon Science Application at Neutrino Factory

K. Nagamine*
Meson Science Laboratory, Institute of Materials Structure Science, KEK, Japan†

By using intense muon beam at the level of higher than $10^{10}/s$, new types of experiments of muon science application will be realized. Based upon recent significant achievements in the related experimental fields, possible future developments in three major directions are considered, namely, the muon catalyzed fusion as a new atomic energy source, the life science studies with the muon labelling method and the disasters prevention with intense muons and neutrinos.

1. Introduction

According to the recent scenario of realization of neutrino factory, there might be an intermediate step of the production and application of intense low-energy muon. In this report, we will consider possible applications of the intense muon to the interdisciplinary science researches other than the fundamental particle-physics. Based upon recent progresses at the world-wide low-energy muon community, we would like to emphasize the following three directions; muon catalyzed fusion, muon labelling method for biological electron transfer and muon/neutrino application for disasters prevention.

2. Muon catalyzed fusion (μCF) as a new atomic energy source

As described in more detail in various review articles, the basic process of μCF in a D–T mixture can be summarized as follows. After high-energy μ^- injection and stopping in a D–T mixture, either $(d\mu)$ or a $(t\mu)$ atom is formed. Because of the difference between $(d\mu)$ and $(t\mu)$ in the binding energies of their atomic states, μ^- in $(d\mu)$ undergoes a transfer reaction to t, yielding $(t\mu)$. The thus-formed $(t\mu)$ reacts with D_2, DT or $T_2$to form a muonic molecule at a rate of $\lambda_{dt\mu}$ followed by a fusion reaction occurring from a low-lying molecular state of the $(dt\mu)$ in which the distance between d and t is sufficiently close to allow fusion to take place; a 14-MeV neutron and a 3.6-MeV α-particle are emitted. After the fusion reaction inside the $(dt\mu)$ molecule, most of the μ^- are liberated to participate in a second μCF cycle. There is however some small fraction of the μ^- which are captured by the recoiling positively charged α. The probability of forming an $(\alpha\mu)^+$ ion is called the initial sticking probability, ω_s^0. Once the $(\alpha\mu)^+$ is formed, some of the μ^- can be stripped from the $(\alpha\mu)^+$ ion and liberated again. This process is called regeneration, with a corresponding fraction R. Thus, μ^- in the form of either a non-stuck μ^- or one regeneration from $(\alpha\mu)^+$ can participate in the second μCF cycle, leading to an effective sticking parameter, $\omega_s : \omega_s = (1-R)\omega_s^0$.

As summarized in the latest conference Proceedings [1], significant progress has recently been marked in the following two aspects, both encouraging increase of energy production capability.

(a) High μCF cycling rate in a high-density D–T mixture

The high cycling rate (λ_c), which is the parameter most sensitive to $\lambda_{dt\mu}$ was observed in a solid D-T mixture, although there have been no theoretical explanations. It is interesting to point out that once the apparent density- dependence continues to hold, a large (λ_c) of $150 \times 10^6 s^{-1}$ can be expected at $2\times$ (liq. H_2 density) corresponding to 660 fusion per μ^- with no muon loss per cycle being achieved.

(b) Anomalous μ^- regeneration from the stuck $(\alpha\mu)^+$ after the μCF

*kanetada.nagamine@kek.jp
†Muon Science Laboratory, RIKEN (Institute of Physical and Chemical Research), Japan

Regarding sticking and regeneration phenomena, systematic measurements of both the X-ray from recoiling $(\alpha\mu)^+$ and the fusion neutrons have been carried out. A consistent explanation for both the X-ray intensity $Y(K_\alpha)$ and the ω_s obtained by fusion neutrons can only be obtained by admitting a larger R than that of theoretical predictions. Furthermore, in solid D–T, by reducing the temperature from 16K to 5K, the data points move towards larger ω_s while keeping almost the same $Y(K_\alpha)$. The result suggests that a larger R (smaller ω_s) can be expected in a pressurized and high-temperature solid D–T.

In order to consider the energy-production efficiency, it is required to know how much energy is needed to produce a single muon. Selecting the values for π^- production in a t–t collision, the eventual cheapest cost might be about 1 $\pi^-/4$ GeV and 1 $\mu^-/5$ GeV. On the other hand, the energy-production capability $(E^m_{\mu\mathrm{CF}} athrmout)$ of the μCF process is determined by $E^{\mathrm{out}}_{\mu\mathrm{CF}} = 17.6 \times Y_n$ (MeV) in the case of D–T μCF, which has a stringent limiting factor due to the ω_s to be expressed as $E^{\mathrm{out}}_{\mu\mathrm{CF}} \leq 17.6 \times \omega_s^{-1}$ (MeV).

In order to decrease ω_s or increase R, several ideas have been proposed, among which the use of a pressurized solid D–T mixture seems to be promising, as indicated above. Similarly, in order to increase R, the use of the acceleration of $(\alpha\mu)^+$ using an electric field and a D–T plasma is expected due to an elongated $(\alpha\mu)^+$ mean-free path are worth trying.

At the era of neutrino factory, no matter how break-even is achieved or not, it is highly expected to realize a μCF reactor producing more than kW energy at the “controllable” and “quiet” manner, which is quite important to obtain “public understanding” for the fusion energy.

3. Life Science of muon labelling for biological electron transfer

The electron–transfer process in macromolecules is an important part of many biological phenomena, such as the storage and consumption of energy and photo-synthesis. Many experimental investigations have been carried out to explore the electron-transfer phenomena in proteins and related chemical compounds. However, almost all the existing information on electron transfer has been obtained by essentially macroscopic methods. In order to understand the details, it is very important to use methods that provide information at a more microscopic level.

Recently, by extending the muon spin rotation/relaxation/resonance (μSR) method we have successfully developed a method to directly observe microscopic aspects of electron transfer. The principle of μSR is based upon the particle-physics law of weak-interactions of polarized muon production via pion-decay as well as asymmetric e^+e^- emission from a polarized muon. Thus, the μSR method can be considered to be a sensitive magnetic compass to probe the microscopic magnetic properties of condensed matter.

In order to obtain a microscopic information on electron transfer in a biological macro-molecule, the muon spin-relaxation (μSR) method offers great potential. During the slowing-down process, the injected μ^+ picks up one electron to form a neutral atomic state muonium. This muonium is then thermalized, followed by chemical bonding to a specific site on the molecule. Then, depending upon the nature of the molecule, the electron brought by the μ^+ can take on several characteristic behaviours, including a localization to form a radical state and/or a linear motion along the molecular chain. These behaviours, by setting the time-origin of electron motion, can be detected most sensitively by measuring the spin-relaxation process of the μ^+ using the μSR method, which occurs through a characteristic magnetic interaction between the μ^+ and the moving electron produced by the μ^+, itself. In other words, in place of “radioactive electron,” by introducing “electron” and an “electron observer” at the same time, the tracer of the “electron” can be made as an alternative manner; the labelled electron method.

Microscopic behaviour of electron-transfer in cytochrome c (with Fe(III)) and myoglobin have been studied in comparison with cytochrome with Fe(II), lysozyme, etc. Measurements between 5 K and 300 K show that the inter-site diffusion rate for the topologically 1D motion along the chain is only weakly dependent on temperature. Evidence for an increase in higher dimensional motion is seen around 200 K in cytochrome c, apparently reflecting a structure change from a glass-phase, while in myoglobin does not have such a property representing the difference between "natural" and "artificial" electron transfer [2].

Electron-transfer phenomena in DNA are known to be important in view of a damage and repair mechanism of DNA, but also a possible application to new bio-devices. A recent experimental finding of possible electron transfer between G bases has accelerated both experimental and theoretical studies. Recently, Yamanashi-RIKEN- KEK-Oxford-Kasei Gakuin-Juelich collaboration, has successfully conducted μSR experiment on oriented DNA in both A and B form of DNA, discovering electron transfer in DNA, somewhat consistent with the picture of an electron hopping through base pairs.

By using positive muon, the labelled-electron method was proved to be a promising probe to explore microscopic aspects of electron-transfer phenomena in biological molecules. The characteristic diffusion time-constant (τ_c) covers from ps/site to ns/site. By considering the value of the average fluctuating hyperfine fields from the moving electrons to the $\mu^+(\omega)$ being $10^7 \sim 10^{10}$ Hz, the relaxation time of the probe estimated by the $(\omega^2\tau_c)^{-1}$ relation becomes in the range from $10^{-9}s$ to $10^{-2}s$, nicely matching to the time-range of muon probe.

4. Compact and intense muon/neutrino source for disasters prevention

Recently use of the near-horizontally arriving cosmic-ray muon as a probe of the inner- structure of gigantic geophysical substances, such as volcanic mountains have been proposed [3]. There, the basic idea can be explained by the following several steps: a) Cosmic-ray muon energy spectrum and its dependence on the vertical zenith angel is almost unique; b) The range of cosmic-ray muons through a rock mountain is uniquely determined by electromagnetic interactions; c) Thus, intensity of cosmic-ray muons (N_μ) penetrating through the rock with thickness of X is uniquely determined; d) Determination of the cosmic-ray muon path through a mountain can be determined by employing position-sensitive detection method.

In order to confirm the feasibility of the presently proposed method, a test experiment has been conducted by employing a simple set-up for the detection of near-horizontal cosmic-ray muons passing through Mt. Tsukuba. Then, the experiment was extended to measure the inner-structure of Mt. Asama where the existence of a volcanic eruption channel is known. There, we confirmed that our method can clearly detect the existence of a channel from an observation point outside the mountain.

Among various applications of the proposed method, the prediction of a volcanic eruption was considered. For this purpose, a volcanic eruption is considered to be preceded by a change in the density along the movement of channel inside the top part of the volcano.

Now let us consider the new direction of the muon-based geophysical studies by employing the idea of re-acceleration of muons from a high-quality muon "ion source" based upon the concept of the ultra-slow μ^+, which has been proposed and realized at KEK-MSL [4]. Recently, it has been noticed that, by combining with the large-solid angel MeV muon source, an intense ultra-slow μ^+ source with an intensity of $10^{12}\mu^+/s$ and an emittance of better than 10^{-7} rad·m can be generated using the following scheme; thick carbon target with a large solid-angle superconducting pion-collector at an external beam line of medium energy followed by a pion decay-section (super-super muon channel) coupled with the ultra-slow μ^+ generator mentioned above.

Thus-produced high-intensity ultra-slow μ^+ can be considered as an ion source for further acceleration of a RFQ and DTL pre-accelerator followed by e.g. a superconducting linac and recirculating accelerator. There, after prompt acceleration up to more than 100 MeV there is a small loss of muons during the process of further acceleration. Thus, an intense and high-quality TeV μ^+ source can be realized. Then, by installing a relevant decay-section for the accelerated μ^+, intense and high quality neutrinos will be produced via $\mu^+ \rightarrow \bar{\nu_\mu} + \nu_e + e^+$, employing the race-track type muon storage ring. The neutrino beam produced has properties due to the kinematics of three-body muon-decay; the decay cone, the opening half-angle, θ_μ, becomes smaller at higher muon energy (E_μ), according the relation m_μ/E_μ.

An intense and high-quality TeV muon beam, with the help of the future intense pulsed proton source (with more than MW power), once it is replaced for the cosmic-ray muons, will be really helpful to study the inner-structure of a volcano. However, this idea has a severe limitation in that the accelerator should be built at a place near to the volcano. Mobile TeV muon source, like on ship, should be considered in the future.

Similarly, once advanced neutrino beam becomes available the neutrino can be monitored via a charged-particle appearance reaction, like $\bar{\nu}_\mu \rightarrow \mu^+$. The use of neutrinos is quite promising to explore the details of he inner-structure of the earth. The neutrino intensity transmitted through the earth for the fixed neutrino energy ($\bar{E}_\nu$) does depend upon the density distribution of the inner-earth structure. With the help of variable value of the average neutrino energy ($\bar{E}_\nu \cong E_\mu/3$)

by changing the muon energy (E_μ), more involved information will be obtained concerning the density as well as element distribution of the inner part of the earth. By employing the advanced neutrino beam proposed here, a time-dependent change of the inner-earth structure might be monitored, providing the most important data-base for the earthquake prediction.

5. Conclusion

As described here partly, glorious future of muon science application is guaranteed. Public accountability and justification of the expensive accelerator project will be obtained by the muon science application.

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