Non-Destructive Muon Analysis for Deep Geological Repositories

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Introduction

Muons (μ) are elementary particles mimicking heavy electrons or light protons.[1] Using a particle accelerator, we can generate and implant negative muons in samples and acquire non-destructive, sub-surface elemental analysis as a function of depth. These methods can be applied to many samples, including deep geological repositories (DGRs) and their used fuel containers (UFCs) for corrosion analyses.

Muon Analysis Technology

Most elemental analyses are limited to the surface, or are destructive, whereas this method is not. Muons are generated via the scheme in Figure 1, whereby protons are accelerated to hit a target, producing pions,[2] which decay into muons and muon neutrinos. The muon's momentum can be tuned to achieve a precise implantation depth (enabling depth profiling) with Monte Carlo simulations (Figure 3); possible depths vary with samples (0.05-11.12 mm in Cu, at Rutherford Appleton Laboratories in the UK). However, larger momenta will yield larger muon scattering and data spread.[2]

Once implanted, muons replace a valence shell electron and move toward atomic nuclei. In energy transitions, muonic X-rays are emitted and detected, which are characteristic of the atomic element.[2]

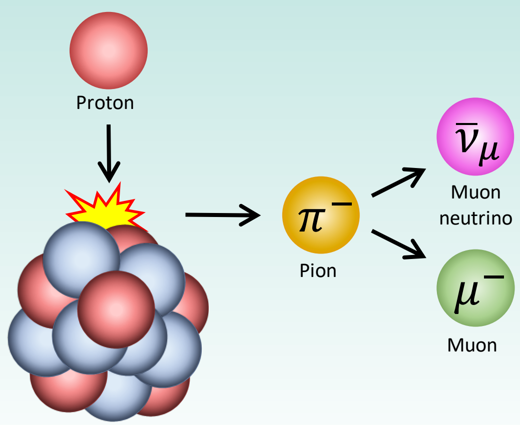

Figure 1: Muon generation scheme.

Previous Applications

These methods have been used on meteorites,[3] biological samples such as tissues,[4] and human spine samples.[5] There are also many cultural heritage applications: ancient Chinese bronze artifacts,[6] Japanese coins,[7] and Roman coins to determine debasement trends.[8]

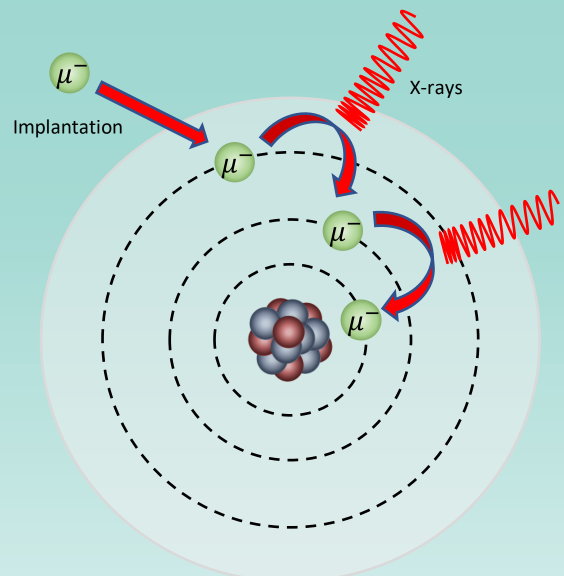

Figure 2: The implantation and energy level transitions of the negative muon in an atom.[2]

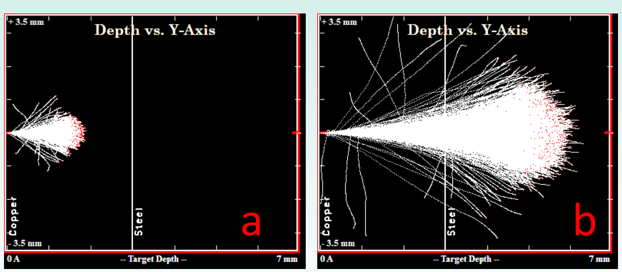

Figure 3: Monte Carlo simulations of muon implantation depths in the UFC using momenta of a) 51.4 MeV/c and b) 73.7 MeV/c.

DGR Applications

Corrosion studies are of interest for studying potential degradation rates of UFCs. The DGR environment exposes the outer copper layer to potential damage, by microbiological, anoxic, and radiolytic corrosion. This corrosion may cause hydrogen absorption, leading to embrittlement or blistering.[9] If we non-destructively analyze the UFC, we can conduct long-term kinetics studies and elemental changes as a function of time and depth to monitor corrosion and hydrogen effects.

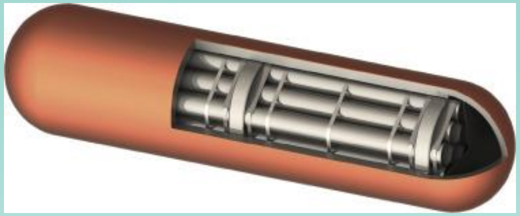

Figure 4: NWMO's Mark II UFC design.[10]

Future Work

The negative muonic X-ray analysis technique can be used to non-destructively probe elemental data under sample surfaces as a function of depth. This gives opportunities for kinetics studies and diffusion studies unfeasible with other analysis methods. Many future corrosion studies of DGR UFCs are possible with the outlined methods, to study longevity and degradation rate of the containers.

References

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